WRDC-TM-90-203-POTX

REVIEW OF AIR FORCE COMPRESSOR BLADE AND VANE REWORK AND IT'S IMPACT ON PERFORMANCE AND COST

MAY 1990

DR ROBERT A. WHEASLER
University of Wyoming

Aero Propulsion and Power Laboratory
Wright Research and Development Center
Air Force Systems Command
Wright-Patterson Air Force Base OH 45433

FOREWORD

This report was prepared by Dr Robert Wheasler, University of Wyoming, for the Compressor Research Facility (CRF). It contains a study of the magnitude of compressor blade and vane rework efforts at the depots and relates these efforts to the potential performance improvements of a jet engine. This report provides a preliminary cost benefit of compressor rework by relating these performance improvements to fuel savings.

The efforts of many people are contained in this report. The author is especially appreciative of the support and cooperation received from the participating organizations at the depots. The author would also like to thank Connie Wagner (POTX) for her assistance in preparing this document.

DOUGLAS C. RABE
Project Engineer
Technology Branch

FRANCIS R. OSTDIEK
Chief, Technology Branch
Turbine Engine Division

ROBERT E. HENDERSON
Deputy for Technology
Turbine Engine Division
Aero Propulsion & Power Laboratory

TABLE OF CONTENTS

INTRODUCTION

The first successful powered flight of an aircraft was a direct result of the development of an engine to propel the aircraft. Since that time engineers have been faced with challenges to develop improved propulsive devices. The use of a gas turbine as a propulsive device for aircraft was introduced to the world as early as 1939 and was heralded as a simplified propulsion device in comparison with the reciprocating engine used up to that time. Although the aircraft gas turbine is based on well-understood principles, the propulsion engineer is continuously challenged to improve on its performance to satisfy the ever-increasing need for high-performance aircraft.

Although the basic principles of the gas turbine engine are understood, its operation seems oversimplified to some. The problems involved in developing a high-performance engine include applications of nearly every engineering discipline. The development of the gas turbine engine to its present stage is a result of the vast amount of research that has taken place during the past fifty years, as was the case in the development of the propeller-reciprocating engine. The demands for a high-performance engine have resulted in a highly sophisticated design which can only be successful through utilization of all the latest technologies.

It was early recognized by the Air Force that the high-performance engines being developed were continuing to be ever more difficult and expensive to maintain. Soon terms and phrases, such as reliability, maintainability, and affordability became standard vocabulary throughout the Air Force. A great deal of emphasis is continuing to find ways in which all services can contribute to the reliability and maintainability of all weapons systems. The maintainability of engines is only a small part of this effort.

Contribution to the understanding of those factors which influence reliability and maintainability of aircraft engines lies fundamentally in an in-depth understanding of all components that make up the complete engine. This includes in-depth understanding of such sciences as aerodynamics, thermodynamics, materials, heat transfer, combustion, vibration, control mechanisms, hydraulics, and pneumatics. It is only through a continued effort to understand the scientific principles involved in the design of aircraft engines that these factors which impact reliability and maintainability can be injected into the philosophy of design.

One of the purposes of the present effort is to gain a better understanding of one of the engine components that has a strong influence on the operation of an engine; i.e., the compressor. In addition to those engineers whose primary function is to design and develop the high-performance engines for the Air Force, there are many whose responsibilities are to assist in the maintainability and reliability of the engines that have been fielded. The production environment in which these engineers operate on a day-to-day basis in most cases leaves little

time to devote to concentration of effort in engine development improvement. The pressures under which they operate and the demands on their time preclude the dissemination of their experience and understanding of engines to those engineers whose prime responsibility is the development of engines. Consequently, a communications gap exists between engineers in the logistics and systems commands. Although this communications gap is recognized by some, and efforts are being made to improve understanding and appreciation of one another's challenges in their areas of responsibility, continued emphasis should be devoted to improvement in these efforts.

There are many problems that arise in the maintainability of engines and must be confronted by the propulsion engineers in the engine depots, which demands that the problems be resolved as quickly as possible. The time constraints on resolution of these problems demand decisions oftentimes based on inadequate background and data. One area of concern that is often voiced by depot propulsion engineers is the question of the magnitude of degradation through normal field usage, how the degradation of one component affects the operation and degradation of other components, and the composite of these influences on the performance reliability and maintainability of these engines.

The importance of the compressor in the performance of an engine is well recognized. Compressor design and technology has attained a high degree of sophistication compared to the early engines, yet there continues to be a need for an increased understanding of the mechanisms of fluid flow through rotating machinery. These factors must be continually investigated if information is to become available which will have a serious impact on influencing the philosophy of compressor design. Propulsion engineers also recognize that in order to understand the operation of a gas turbine engine, the characteristics of each component must be understood. The basis for successful design of the gas turbine engine lies in the understanding of the characteristics of the individual components. It is only through an accurate determination of the operating line that the performance of engines can be predicted, which is an absolute necessity in the determination of the aircraft performance. Consequently, the understanding of the operation of the compressor is of primary importance to the propulsion design engineer, although this is not always appreciated.

For example, through experience in the design of gas turbine engines and association with both the logistics and systems commands, comments have been received from engineers having managerial responsibilities in the engine depots, questioning the continued need for devoting time and energies to understanding of compressors where problems exist in other components of the engines, namely the "hot section". These comments at times are influenced by pressures placed on engineers to resolve problems that surface in maintaining the "hot section" of engines. It tends to be an area most demanding on their time. They feel seriously in need of assistance in an effective, timely resolution of their problems. However, I have sensed that some have failed to recognize that some of the problems

that surface in the "hot section" are influenced by the way in which the compressor is operating. Since all components interact, it is necessary to gain as much understanding of individual component operation as possible, if one is to develop a capability to isolate faults/deficiencies that occur during the operation of engines. The interest being developed in improving the understanding of losses that occur during normal engine usage is recognized as being only one approach through which contributions could be made to improvement of an engine. For example, a decrease in the adiabatic compressor efficiency, considering other parameters constant, will in general result in a decrease in net thrust, an increase in specific fuel consumption (SFC), and an increase in turbine inlet temperature, in addition to impacting other engine parameters.

In order to provide information on the question of how the degradation of a compressor from its original design condition, resulting from normal usage, affects other engine parameters, an effort has been underway to determine what information is available to assist an engineer in decision making. At this point in time it appears that no major effort has been made to quantitatively determine the magnitude of these losses, where they occur, and the mechanisms that contribute to these losses. The information gained so far has indicated that the majority of the efforts to assess these losses have been based on theoretical analysis of flow mechanisms and test data accumulated on one-, two-, and three-stage "test rigs".

In addition, engine manufacturers have provided propulsion engineers in the field with information to assist them in evaluating and predicting losses in engines through data termed as Performance Influence Coefficients. Since knowledge of how these parameters and coefficients have been developed has not been made available for this study, it is assumed that these data are a result of a combination of regular testing, theoretical analysis, and the best engineering judgment available. The present investigation has, therefore, not revealed any major effort to measure quantitatively the aforementioned losses. Therefore, there appears to be insufficient information on which to assess degradation in engine performance with a degree of reliability that would contribute to the decision-making process confronting those involved in improving the reliability, maintainability, and affordability of engines.

The Compressor Research Facility (CRF) that has been developed in AFWAL has the sophistication and capability to acquire the information needed to explain losses in compressors. The thirst for technology in all fields of aircraft and engine performance demands careful programming of the utilization of research facilities available to the Air Force. The CRF has proved to be a great asset in contributing to compressor technology, but it will continue to have many demands on its use. Consequently, priorities for its use must be carefully evaluated prior to any commitment for the development of a proposed test. Although the determination of losses occurring in compressors is of considerable importance, it is recognized

that the degree of importance must be weighed against other priorities, it is only prudent to determine from an economical standpoint whether any test will justify the necessary expenditure of funds. One must recognize that it is difficult to determine the comparative monetary value of improving design through an in-depth understanding of compressor operation, relative to conforming to the present engine management philosophy.

A portion of this philosophy has been influenced by the necessity of reworking blades and vanes, which presently is considered to be a cost-effective approach in engine overhaul. Herein lies an important factor that must be carefully weighed; that is, to what extent the knowledge exists to adequately assess the cost factor in the current rework methods with their accompanying designated acceptable limits of rework. The question still remains as to the degree of knowledge available to assess the influence of the apparent degradation on other parameters of engine performance, such as thrust, SFC, and turbine inlet temperatures.

One must recognize that the most important question to emphasize is <u>not</u> the comparison of whether to rework (blend) compressor blades and vanes, but to develop quantitative information which will enable the determination of the change in compressor component variations from the original nominal design characteristics. These variations occur as a result of normal field use of engines during their life cycle. Consequently, these changes will influence other engine component characteristics--which impact life cycle costs (LCC) of the engines in the Air Force inventory.

One of the objectives of the present investigation was to determine the magnitude of compressor blade and vane rework effort in the depots. One facet of the blade and vane rework study was to gain an insight as to the established accepted limits on blending of blades and vanes, with regard not only to the amount of blending, but also the numbers that are condemned due to other factors--primarily cracks. It is intended that this will provide information regarding the effect of blending on deviation from original design, which could also provide information in considering extending these limits for economical reasons. The present management practices do not require the maintenance of records that will make this information readily available. Consequently, it was necessary to make a special effort to acquire this information at those locations where blades and vanes were being reworked.

It was soon found that the acquisition of data which would give a complete assessment of the magnitude desired from a practical standpoint would necessitate the acquisition of a sufficient sampling of data in order to present a reasonable appreciation of the work being accomplished in the depots. Acquiring even a minimal amount of data requires the cooperation of many individuals in the air logistics center, and in many instances imposes on their valuable time to assist in an effort which is not a portion of their routine responsibilities. Many individuals were interested in the results of such an effort, appreciated its importance, and assisted in providing the information needed. However, their time and

priorities did not always enable them to provide the required information. The Oklahoma City Air Logistics Center proved to be extremely cooperative in assisting in the project, particularly recognizing their constraints. The Propulsion Management Division in San Antonio Air Logistics Center (SA-ALC/MMP) was also very cooperative and contributed greatly to the project.

It was learned during the investigation that a report had been developed by personnel in AFLC/MAQ which addressed the value of the blade and vane rework effort in the engine overhaul facilities. It is understood that this report included justification for the necessary rework facilities. Attempts made to obtain information from this investigation which would provide important additional data have been unsuccessful to date.

In reviewing the rework effort, considerable time was devoted to researching available information which addresses losses in engine performance, particularly the influence that these losses have on the increase in SFC which translates ultimately to increased fuel cost, decreased meantime between overhauls, and loss in range and payload of aircraft. The reports available have been, in almost every case, a result of engine manufacturers' response to Air Force or commercial airline needs to improve SFC, or proposals submitted to the Air Force by engine manufacturers for modifications to existing engines which are intended to reduce life cycle costs (LCC) through improvements in SFC, "hot section" life, etc. It is necessary that the best available data be supplied to those individuals responsible for determining the value of the proposals. It is this kind of data that can only be obtained through continued efforts to acquire a better understanding of scientific principles.

Approach to the Project

Visits were made to the OC-ALC and SA-ALC maintenance facilities in order to acquire data on the blade/vane blending operations. In addition, some information was made available for the repair costs, new blade/vane costs, and condemnation rates, in order to develop an appreciation of the magnitude of the blade/vane rework by the Air Force. One of the objectives was to isolate the vane/blade blending condemnations versus those rejected as a result of cracks--including foreign object damage (FOD).

Shop specification drawings for each blade and vane stage were obtained for the J-79, TF-30-P-9, TF-33-P-7, TF-39, and T-56 engines. These specification drawings were scrutinized for manufacturer's tolerances, with particular regard to the tolerances for chord span, blade/vane thickness, and leading and trailing edge contours, in order to gain an insight into the variations in blades/vanes that could occur between average new parts in the fleet, and to acquire information which would assess the percentages of deviations from the nominal new part dimensions as a result of accepted rework practices. Then, considering the magnitude of compressor design variations through blade/vane rework, the anticipated losses in compressor component efficiencies and the corresponding impact these efficiency decreases would have on other engine parameters, particularly the thrust specific fuel consumption (TSFC) and the turbine inlet temperature (TIT) would be assessed. Additional attempts were made to evaluate in part these influences on range, payload, and fuel costs for representative aircraft in the Air Force fleet.

Blade/Vane Rework Analysis

The following information is available as a direct result of the effort of the Maintenance Directorate Compressor Blade/Vane Rework Section and the OC-ALC/MAENF at Tinker Air Force Base, Oklahoma, and the SA-ALC/MMPARE (TF-39) at Kelly Air Force Base, Texas. Information was collected by the compressor blade/vane rework shop personnel at Oklahoma City for the month of August, 1988. They recorded a count of the blade and vane rework for each engine, identifying the number of blades that were suitable for rework within the TO limits, recording those that were condemned as a result of exceeding blending limits, and differentiating between those rejected for detection of cracks, and those rejected as a result of foreign-object damage (FOD). The results of their tabulation of blade/vane rework efforts are summarized below:

TF-41: for the month of August 1988, there were 9,309 blades reworked and 668 not repairable because they exceeded TO blade limits. The annual blade cost, if all new blades were used, would be $24,634,275 and $2,960,387 if repairable, or an 87.98 percent savings through repair. It should also be noted that through the design of the engine there are high-cost items that are not generally in need of repair. Therefore, based on past experiences, the average cost savings over the new purchase required (condemned) plus rework costs is 38.53 percent, or $1,855,758 dollars annually, for a fleet of 356 installed engines.

J-79-15/17: the most extensive data available for the blade/vane rework effort was for the J-79-15/17 engine, due particularly to the contribution efforts of the J-79 engine group at Oklahoma City, in addition to OC-ALC/MAENF and the compressor blade/vane repair section at Oklahoma City. If all blades were replaced for the J-79 engines going through overhaul at OC-ALC, the annual cost would be $26,066,929 dollars, and if the present accepted rework practices are continued, the total cost of the rework effort, plus the purchase of new blades that are required to replace those condemned would be $11,799,301 dollars, or a savings of $14,267,628 dollars, a savings of 54.73 percent.

TF-30: evaluation of the blade/vane rework (based on the month of August, 1988) indicate 2,835 blades/vanes reworked, and 319 condemned because they exceeded TO rework limits, or 89.9 percent usable for rework.

TF-33: for the month of August 1988, 11,991 blades/vanes were reworked, with 290 condemned because they exceeded TO limits (2.42 percent condemnation).

J-57: for the month of August 1988, 11438 blades/vanes were reworked, with 1,186 blades/vanes condemned because they exceeded TO blending limits (10.37 percent).

Summary for month of August 1988: the overall production rate for reworked blades and vanes - 78,427, condemnation rate (exceeding TO limits) 9,838 blades/vanes, or 12.54 percent not repairable. 100 blades/vanes were rejected, attributable to FOD damage.

It should also be noted that blade/vane rework for each engine managed by the OC-ALC varies monthly, dependent upon the accumulation of blades and vanes that require rework during any particular period of time. In addition to the Oklahoma City blade/vane rework effort, some information was obtained from San Antonio ALC, namely for the TF-39. Much of the blade/vane rework at San Antonio is contracted out. The blade data for the TF-39 compressor that was available indicated that the annual number of blades purchased to repair engines at the depot for the sixteen stages is 13,152, and 26,286 that do not exceed the TO repair limits are repaired; that is, 57.1 percent repaired. The annual new blades required, plus those blades repaired for the TF-39 engine at SA-ALC (those not contracted out) represent a cost of $1,781,479 dollars, and the annual cost if all new blades were to be used would be $2,850,923 dollars, or a 37.51 percent savings through rework.

The above savings should, of course, also be compared to the impacts on performance, fuel consumption, and engine parameters, as well as life-cycle-cost (LCC) of engines in the fleet as a result of the blade rework efforts. No attempt was made to acquire statistics on foreign object damage (FOD) for Air Force engines; however, the following information has been included in order to gain some insight into the relative magnitude of the rework effort for reasons other than FOD.

The actuarial data for March 1988, indicate that there are 977 J-79-17 engines and 2413 J-79-15 engines installed, for a total of 3,390 installed engines. The average overhaul rate, based on a two-year average (1986-87), is 441, and the average number of engines removed for FOD for both the fifteen and seventeen is 15, or 0.443 percent of installed engines receiving FOD damage. For the TF-41 there are 356 installed engines, at an annual rate of 46 overhauls at the depot, and one engine annually receiving FOD damage, which is 0.281 percent of installed engines receiving FOD damage. Also, the shop-visit rate for the J-79 on the average is 7.69 years per engine, and for the TF-41 is 7.74 years per engine.

In addition to the losses incurred by compressors as a result of blade/vane erosion, seal wear, airfoil contour changes, etc., surface condition (roughness) has been considered to be important; therefore, a review of the literature on the subject was made and a few comments seem to be in order.

For several years (reports/correspondence have been acquired on the subject as early as 1973) attention has been given to various compressor blade and vane surface coatings and corrosion-protective metals. As a result, many studies have been made to evaluate/predict the improvements in component efficiencies by reduction of surface roughness through the applications of coatings. One such study indicated that improvement in blade/vane surface roughness from 70 micro-inches to 44, 20, and 13 micro-inches would result in corresponding improvements in component efficiencies of 1.45 percent, 1.62 percent, and 1.87 percent for the fan, LPC, and HPC, respectively, for the TF-33-P-7. Evaluation of cost effectiveness of fan/compressor blade

and vane coatings continues as a result of variations in opinions on the subject. As an example of the continued efforts to improve surface conditions, correspondence from United Technologies--Pratt and Whitney, dated February 3, 1987 to OC-ALC/MAENE, on the subject of fluid wash of jet engines suggests that as much as 20 degree Fahrenheit improvement in EGT has been reported through its use by United Airlines, and with an average of all operators of 7 degrees Fahrenheit improvement.

Some Analyses of Compressor Degradation on Engine Performance

Effects of compressor component efficiency improvement on SFC and TIT or EGT have been extrapolated from various studies. Differences were found to exist between reported influences of fan/compressor component efficiencies on engine parameters such as SFC and TIT/EGT, both individual component influences and factors (losses) contributing to engine component efficiencies such as tip clearances, seal losses, airfoil contour change, or in general--blade/vane rework. The data accumulated for the project was incomplete for all engines in the Air Force inventory, and although the acquired information was less than ideal, the data that could be acquired within a reasonable time was considered adequate to meet the objectives for the study (project).

Pratt and Whitney Aircraft Group developed a study to determine possible methods for improving the thrust specific fuel consumption (TSFC) of engines on the C-141 aircraft. This study resulted in a report entitled "A Feasibility Study on Improving the Thrust Specific Fuel Consumption for the TF-33-P-7-7A Engines," dated 18 August 1980. Considering only those portions of the report relating to the fan, LPC, and HPC, a one percent increase each in the fan, LPC, and HPC will result in a decrease of 1.7831 percent in the TSFC. These values can be translated to the C-141 aircraft performance at cruise conditions (Mn = 0.75 at 35000 feet) as follows:

1. A fuel savings of 10.873 million gallons per year

2. Increase in range of 78.3 nautical miles at constant gross weight

or

3. Increase in payload by 1738 pounds at constant range

4. Decrease in the turbine-inlet-temperature by 14.5 degrees Fahrenheit (EGT, 17.2 degrees Fahrenheit)

At take-off conditions the TSFC improvement would increase 30.4 percent over that of the cruise improvement, and the EGT would decrease an additional one degree Fahrenheit to 18 degrees Fahrenheit. (Note: The above is based on the C-141 fleet using 600 million gallons of fuel per year). The annual distribution of the total fuel usage in the Air Force varies from year to year. The most recent values were not readily available; therefore, data was extracted from reports available for the same approximate time period as the C-141 study indicated above, and it is this information that has been used for comparison in this investigation, as it is considered to be fairly representative of today. Therefore, the annual fuel distribution is listed as follows:

F/RF-4 aircraft	- 15.8 percent	(607.69 million gallons)
C-141 aircraft	- 15.6 percent	(600 million gallons)
B-52-G/H aircraft	- 13.9 percent	(534.62 million gallons)
KC-135 aircraft	- 12.1 percent	(465.38 million gallons)
All others	- 42.6 percent	(1638.46 million gallons)

Total annual Air Force fuel usage: 3846.1538 million gallons.

The Pacer Grade Study indicates that 16 percent of the B-52 fleet are H-models, using TF-33 series engines. Considering the differences in thrust specific fuel consumption (TSFC) between the G and H models, calculations indicate that 26.8 percent of fuel is used by the B-52 fleet; i.e., 143.4202 million gallons per year. Extrapolating TF-33-P-7 data from the C-141 study to the B-52-H, a one percent increase in the fan/compressor component efficiencies would improve (decrease) the cruise TSFC's of the B-52-H and provide a fuel savings of 852,000 gallons per year. Improvements in other aircraft performance factors such as payload and range could be determined in a manner similar to those indicated for the C-141.

Additional calculations were performed which are intended to provide some insight into the possible effects of blade/vane rework (blending) on engine performance. The approach used was to review the shop specification drawings that were obtained for each blade and vane stage for the J-79, TF-30-P-9, TF-33-P-7, TF-39, and T-56 engines. These specification drawings were scrutinized for manufacturer's tolerances, with particular regard to the tolerances for chord span, blade/vane thickness, and leading and trailing edge contours, in order to gain an appreciation for the variations in blades/vanes that could occur between average new parts in the fleet, and to acquire information which would assess the percentages of deviations from the nominal new-part dimensions as a result of accepted rework practices. Then, considering the magnitude of allowable compressor design variations through blade/vane rework, an assessment of the anticipated losses in compressor component efficiencies was made and calculations were performed to determine the corresponding impact these efficiency decreases would have on other engine parameters, particularly the thrust specific fuel consumption (TSFC) and the turbine inlet temperature (TIT).

Additional attempts were made to evaluate in part these influences on range, payload, and fuel costs for representative aircraft in the Air Force fleet. For example, it was found that for the TF-33-P-7 engine (used in C-141 aircraft) a 10 percent chord reduction in the stage one blade is 0.380 inch, 0.240 inch for the second-stage vane, decreasing to 0.070 inch

for the stage fifteen blade. Technical Orders (TO's) addressing blade and vane inspections will permit chord reductions for some engines up to 18 percent, with most in the 10 to 12 percent range, and 10 to 15 percent reduction in maximum airfoil thickness.

The General Electric Company developed data on the CF-6 and CF-6-50 high pressure compressor to be used to evaluate the influence of tip vane/blade and chord erosion (chord reduction from nominal) on compressor efficiency. Tables were given indicating the change in compressor efficiency due to vane hub land clearances as well as for blade tip clearances. In addition, the report stated that a 0.003 inch chord reduction is equivalent to 0.001 inch clearance effect. Although the General Electric data was developed for the CF-6-50 user, the information was considered a viable approach for estimating losses in other compressor designs. General Electric also offered an additional simplified method for estimating losses and stated, "An average chord reduction over the entire compressor is 0.00072 percent HPC efficiency for each 0.001 inch average chord reduction per stage."

The General Electric report stated that although the allowable chord losses are in the range of 10 to 12 percent, they recommend keeping the chord reduction between 2 and 4 percent. This was particularly interesting since this investigation revealed that the specification drawings for nearly all the engines reviewed have <u>chord tolerances</u> in the 2 to 4 percent range, which suggests that no blade/vane rework be performed.

Some examples are being presented in order to develop an appreciation for some of the influences that blade and vane rework practices have on reduction in component efficiencies and their corresponding impact on engine and aircraft performance and costs. These illustrations are based upon the reports described above which were developed by Pratt and Whitney and General Electric for their special-purpose studies.

The first illustrations consider the effect of blade/vane rework on the TF-33-P-7 engine and the C-141 aircraft performance. The following calculations are based upon four assumptions:

(1) The average chord reduction (from nominal design) for all stages is considered to be 10 percent--this corresponds to an average of 0.159 inch per blade (5/32 = 0.1563 inch).

(2) The blade/vane clearances average 0.030 inch, which is equivalent to the manufacturing tolerance.

(3) 25 percent of each stage have been reworked (blended).

(4) Pits, dents, leading/trailing edge contour rework, and airfoil thickness deviations are not included.

It should be emphasized that these assumptions present a conservative picture of losses that can occur as a result of seal/tip clearances and other accepted blade/vane rework procedures. Scrutinizing all blade and

vane specification drawings for the TF-33-P-7, the average blade and vane chord was equal to 1.596 inches. Note that 3/32-inch blending on the leading and trailing edges would be equivalent to 11.75 percent reduction in chord, which is well within allowable limits for any engine.

Based upon the data and methods available to evaluate compressor efficiency losses described above, and with the assumptions listed, the calculations indicated 2.658 percent decrease in compressor efficiency when using the first approach and 2.79 percent using the second approach. Using the smaller of the two values calculated (2.658), 0.5944 percent TSFC increase per 1 percent decrease in compressor efficiency, and 6.097 million gallons used per year for each 1 percent increase in TSFC equates to 9.633 million gallons of fuel used per year for the C-141 fleet. Other calculations show that the 2.658 percent loss in compressor efficiency is equivalent to 69.36 nautical-mile range loss at constant gross weight per aircraft, or 1540 pound loss in payload at constant range. In addition, an increase in turbine inlet temperature of 26 degrees Fahrenheit could be expected.

Assuming only ten percent of the aircraft in the fleet have blade blending to the extent assumed in the conservative value used in this example, the additional annual fuel cost would be $963,000 dollars (using one dollar per gallon of fuel).

However, when making comparisons of fuel cost as a result of and vane rework cost savings, it should be borne in mind that the C-141 engines return to the depot maintenance shops about once every seven years (Engine Depot actuarial data). Consequently, the increased fuel cost to be used for rework cost comparisons should be $6,741,000 dollars. Since blade/vane rework cost savings data for those TF-33 engines used in the C-141 fleet were not readily available, no comparison was included in this report.

The above discussion was directed to the C-141 fleet, but one should not lose sight of the fact that there are other TF-33 series engines installed in Air Force aircraft; namely, B-52-H (768 versus 1100 C-141 installed engines), E-3A, KC-135B, AND EC-135.

Calculations for the J-79-15/17 (F/RF-4 aircraft) were performed in the same manner as illustrated by the TF-33-P-7 (C-141-A/B) example, with a decrease in component efficiency of 2.76 percent and an increase in specific fuel consumption (SFC) of 1.544 percent, or using the second method as discussed above, the decrease in component efficiency is 3.03 percent, with a corresponding increase in specific fuel consumption (SFC) of 1.8023 percent.

For the 3,390 installed engines in the F/RF-4 aircraft fleet, the total annual fuel used is 607.69 million gallons, or 179,260 gallons per engine. If the fuel consumption were improved by 1.54 percent, the annual fuel savings for an engine would be 2,760.6 gallons, equivalent to 21,229 gallons per engine shop visit. Note that the cost of reworked blades and vanes per a shop visit is $26,755.78 dollars per engine, and the additional cost in fuel due to the allowable blade rework practices is calculated as

$21,229 dollars (based on one dollar per gallon fuel cost). Also, as in the TF-33 example, the anticipated average increase in turbine-inlet temperature for the J-79 engine is 28 degrees Fahrenheit.

Although the illustrations were not precise and include many assumptions, the magnitude of the blade/vane rework effort in the Air Force and its potential impact on engine performance and life-cycle-cost (LCC) should be evaluated carefully with the best information obtainable. Certainly the information/data presently available leaves a great deal to be desired.

Discussion

As indicated earlier, blade and vane rework data was not obtainable for all engines in the Air Force inventory. The data was obtained for the following engines: TF-33, TF-30, J-79, TF-41, plus limited data on the TF-39. The calculations were made to show the number of blades and vanes reworked for the month of August 1988. In some cases, calculations were included to project annual cost savings, although the actual count made by personnel at Oklahoma City was only for the month of August. Additional information was based on actuarial data, assuming the data obtained for the month of August was sufficiently representative to project reasonable cost on an annual basis.

It has become apparent that there is a considerable cost savings through rework of blades and vanes, compared to replacement with new blades and vanes. However, it should be pointed out that the information available for calculations did not indicate clearly whether the rework cost included overhead and amortized facilities-attrition costs.

In reviewing the blend limits for several engines, the results indicate considerable deviation of blade and vane design characteristics from the original specifications. This data was obtained from detailed examination of blade and vane drawing specifications for the following engines, TF-33-P-7, TF-30-P-9, J-79-15/17, T-56, and TO inspection limits and procedures for these engines, as well as for the F-100 and the TF-41. The reported values for deviation of design characteristics from original specifications are comprised of two parts: (1) those attributable to allowable tolerances during manufacture, and (2) deviations allowed through blending. In review of the tolerances allowable during manufacture, it was found that in general there were similar tolerances by the three engine manufacturers, Pratt and Whitney, General Electric, and Allison Division of General Motors. It was interesting to note that the TF-30 and the TF-33 engine tolerances were identical, which might be anticipated, due to the similarities in design of the two engines. However, it was also interesting to note that the allowable tolerances in the chords of all stages from the roots to the tips had the same percentages of chord, that is 2.4 percent variation in chord, regardless of the stage. This was also true in the tolerances allowed in blade thickness during manufacture. However, regardless of the manufacturer, specifications carefully address allowable tolerances required to maintain similar airfoil contour.

Similarities in blending limits were found for all manufacturers as well. From the analysis, it should appear that the airfoil characteristics, such as aspect ratio and blade thickness, were of less importance than airfoil contour and span-wise twist of blades and vanes. This suggests, perhaps, the similarities in the design philosophy of those engines reviewed.

An attempt was made to acquire the solidity of those engines reviewed, but this information was not available without considerable time and effort to locate and evaluate the information. Therefore, care should be exercised in drawing any conclusions as to the effect the apparent appreciable deviation from original design characteristics would have on the degradation of compressor performance.

If one accepts information on original design deviations reported by engine manufacturers regarding their influence on engine performance as having a high degree of accuracy, the allowable blending limits and tolerances for the manufacture and overhaul of engines in themselves would result in loss in performance that would suggest need for a careful review of the resulting costs of the present overhaul practices. These losses are reported to have considerable influence on thrust, SFC, and turbine inlet temperatures, which have been calculated for the manufacturer and translated to increase in fuel costs and aircraft range and payload. This is further indication of the importance of obtaining the best information available. It is also recognized that the decisions made when evaluating proposals to redesign or perhaps re-engine aircraft are based on many factors other than cost alone. This is particularly important for the military decision makers, as oftentimes the decision must be based not only on present military capability but on the ability to meet anticipated threats. Rational decisions are impossible unless all factors which impact the results are considered.

Engine diagnostic systems constitute another area of importance for having the best information available. These systems can be improved with refined data which would support the determination of "influence coefficients." Data providing information regarding compressor map modifications (degradation) as a result of seal and tip losses, and changes in airfoil contour, chord, and surface conditions would greatly enhance the accuracy of aero-thermo-dynamic gas-path analysis. Theoretical gas-path analysis can only be as valid as the available data; that is, the engine must be accurately modeled with realistic parameters depicting the components' characteristics. Obviously the accurate location of the engine's operating line and its deviation from the nominal is essential if fault analysis techniques are to be meaningful.

Conclusions and Recommendations

Based on the available information, it was concluded that efforts should be made to establish the priority that will allow the investigation of the magnitude of losses in compressors and their impact on engine operation and parameters. This information should be obtained by instrumenting a compressor in the CRF designed to determine the magnitude and characteristics that affect the compressor map as a result of variations in such things as aspect ratio, solidity, surface condition, tip losses, and seals. A preliminary consideration of possible candidates for testing indicate the desirability of instrumenting a compressor of the General Electric F-101 engine that is used in the F-110 series engine which has similar characteristics to the F-101 engine that is used in the F-16 and the B-1, respectively. If a compressor can be made available for testing, this would be particularly advantageous, since these engines incorporate the present compressor technology and are projected to be used well into the twenty-first century. As an alternate, it is recommended that the high-pressure compressor of the TF-39 be carefully reviewed as a candidate, since the TF-39 is being projected for continued use for the C-5 aircraft, also into the twenty-first century.

The above-mentioned engines have the advantage of variable guide vanes and a split-case, which will facilitate the changing of the blades and vanes that are envisioned to be necessary to provide variation in blade and vane characteristics to meet the objectives of any proposed test to acquire the desired information. It is envisioned that a test designed to determine the variations of blade and vane design characteristics would result in a compressor map that could be compared with a map that was obtained using all new blades, vanes, and seals. Assuming that other engine component characteristics are available through cooperation with General Electric, such as nozzle, turbine, fan, and combustor characteristics, the calculated equilibrium operating line for the engine with the new parts could be established. Using these same engine component characteristics, an engine equilibrium operating line can also be calculated for the modified compressor. The engine performance parameters can be compared for the two compressors, thereby determining ways in which the variations in compressor maps influence such parameters as SFC, thrust, turbine inlet temperatures, rotor speeds, and other component efficiencies.

It was considered desirable as part of this investigation to acquire information that would show the influence of adiabatic compressor efficiency on other engine performance parameters. In order to do this, the engine characteristic maps would be essential so that a thermodynamic cycle analysis could be performed in such a manner that all parameters other than compressor efficiency could be maintained constant, while varying the compressor efficiency. This would necessitate varying certain conditions, such as altitude, Mach number, and throttle positions, in order to develop a comprehensive evaluation.

The only engine performance data available was for the TF-39 engine. Although these data could provide the engine performance information at a variety of altitudes, Mach numbers, and throttle excursions, they obviously could only provide information that is constrained by the TF-39 engine equilibrium operating line. Consequently, the flexibility of varying compressor efficiency while maintaining other parameters constant is not possible with available data. However, graphs are included for three conditions; namely, sea level static, altitude of 41,000 feet, Mach number 0.785; and altitude of 35,000 feet, Mach number 0.8. These have been included to give an indication of the variations in SFC, turbine inlet temperature, and thrust, with variations in compressor efficiency. This in no way should be interpreted as indicating the effect the degradation of compressor efficiency would have on parameters. It only serves to emphasize the importance of acquiring a "degraded" or "modified" compressor map, as a result of compressor design characteristics, and its resulting equilibrium operating line.

In summary, the following steps are recommended:

1. Initiate a detailed test program in order to evaluate the effects of deviations of compressor design parameters from their original design philosophy on the resulting performance (compressor map) and the consequential impact on other engine parameters that lead to reduced life-cycle-costs (LCC) of engine ownership.

2. Continue with an increase in the effort to inform the executive leadership in AFLC of the importance of, and gain their support for, continuing research activities which will provide the best quantitative information available on the design, maintenance, and performance of compressors. This can, in part, be accomplished by assuring that the propulsion engineering staffs at the ALC's, AFLC, ASD/YZL, and AFWAL understand the importance of the objectives and include the "need" in the Air Force Logistics Needs review and evaluation, which could have considerable impact on acquiring visibility and successful consideration for obtaining an early priority for the CRF use.

3. Continue to accumulate information/data as necessary to substantiate the need for obtaining the desired test data as alluded to in Recommendations Numbers 1 and 2--acquire the priority necessary for the use of the CRF at the earliest time practical.

4. As a preliminary to conducting the proposed test in the CRF: (a) Using a generic engine with an established equilibrium operating line, perform a thermodynamic analysis which will enable the calculation of engine performance at various off-design operating conditions; that is, at different altitudes and Mach numbers. (b) Redevelop the generic engine by judiciously altering the compressor map only (not the other component maps) in a manner which would reflect expected degradation in characteristics resulting from field use and maintenance practices. Then perform additional thermodynamic analyses in order to assess the influences of the modified compressor map (different compressor efficiencies) on various

engine parameters, such as SFC, net thrust, N and N rotor speeds, turbine inlet temperatures, and airflow. The purpose of this recommendation would be to establish the feasibility of determining influence coefficients on engine parameters (variables) as a result of the anticipated information which would be gained through CRF testing, and sensitivity of the measurements required.

Note: This recommendation assumes that a potential CRF test article (compressor) has not been selected and is suggested as an alternate to obtaining characteristic plots of the compressor, turbine, nozzle, etc. from the manufacturer of the proposed test article during the interim period.

APPENDIX

List of Figures

Examples of Blade and Vane Rework (Blending) Areas, Figures 1 through 3, are included as illustrations of vanes and blades that are typically found in any engine after rework (blending) - darkened areas represent blended regions. Examples of maximum allowable rework regions have not been shown as they vary, not only from stage to stage, but from engine to engine, although they are similar for all engines.

Performance Curves for TF-39 Engine (C-5 Aircraft)

The following figures (4 through 18) are based on General Electric TF-39 performance data. It should be emphasized that the "crossplots" - High Pressure Compressor Efficiency (ETA) versus Turbine Inlet Temperature (TIT) and Thrust Specific Fuel Consumption (TSFC) have been developed by crossplotting points of constant values of percent of Low Speed Rotor ($\%N_1$). Consequently, the resulting curves represent variations in the listed parameters as dictated by the equilibrium operating line - not a "degraded" compressor (as indicated in the text of the report).

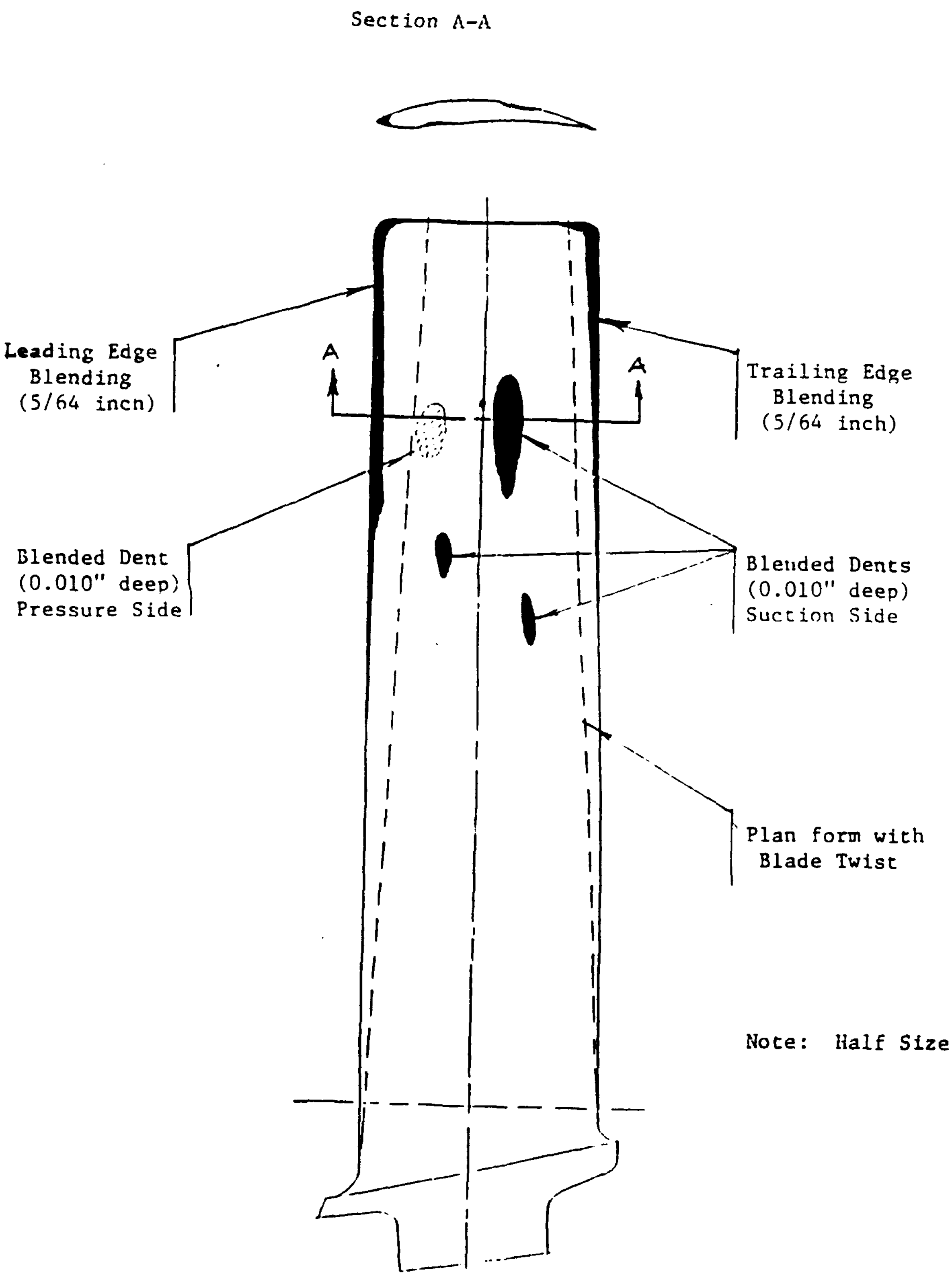


Figure 1. First Stage Vane, J-79-15/17

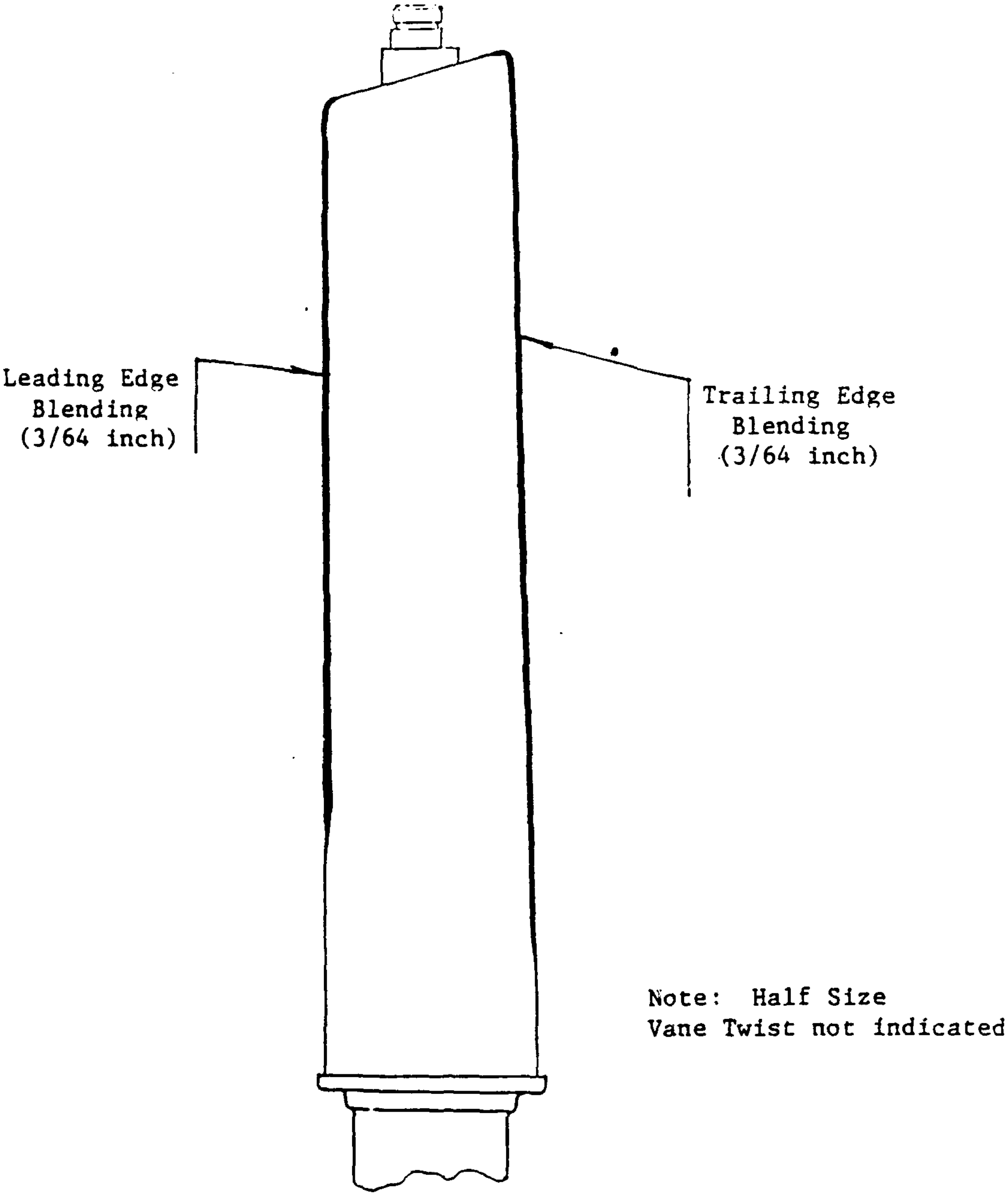


Figure 2. First Stage Variable Vane, J-79-15/17

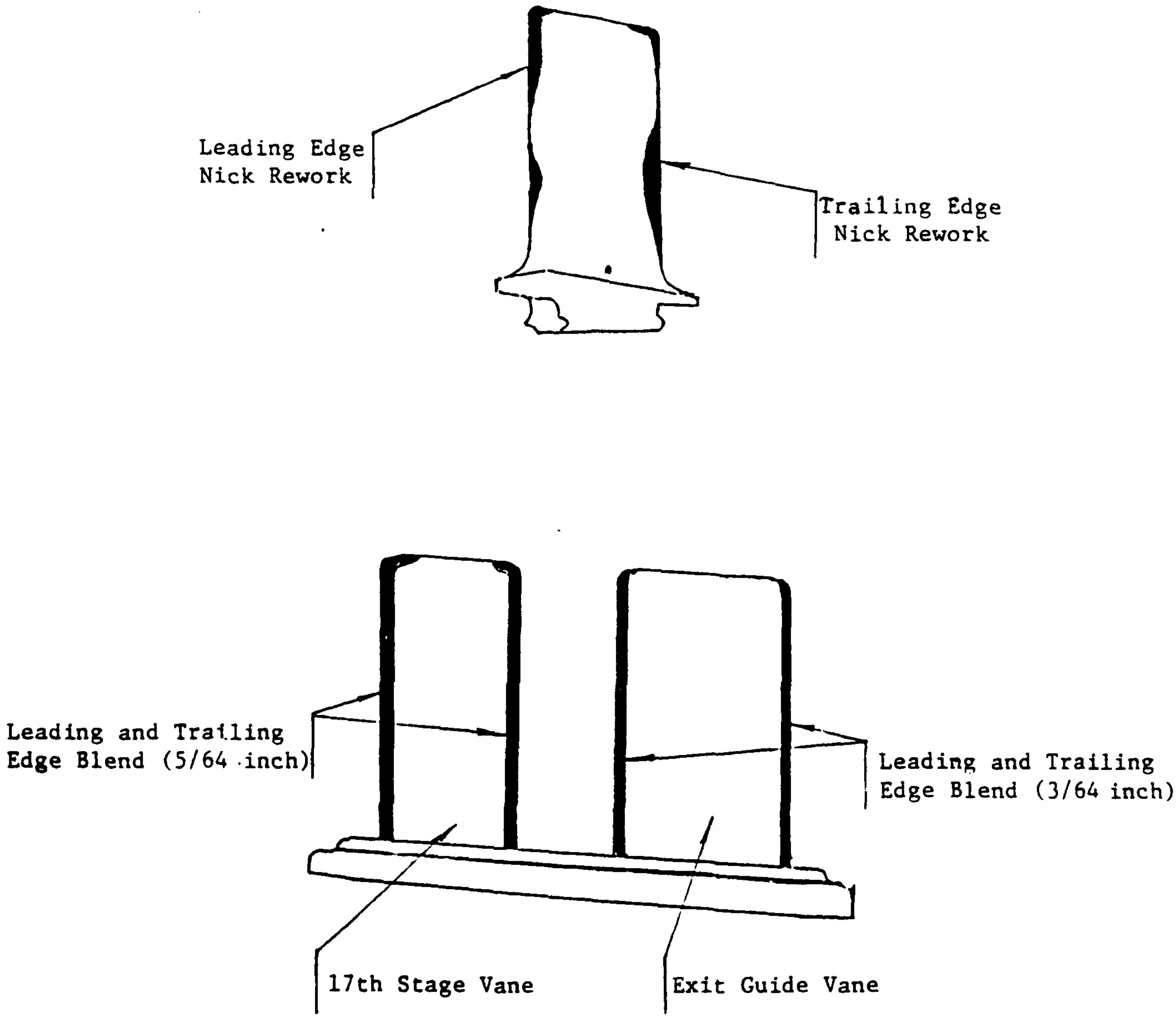
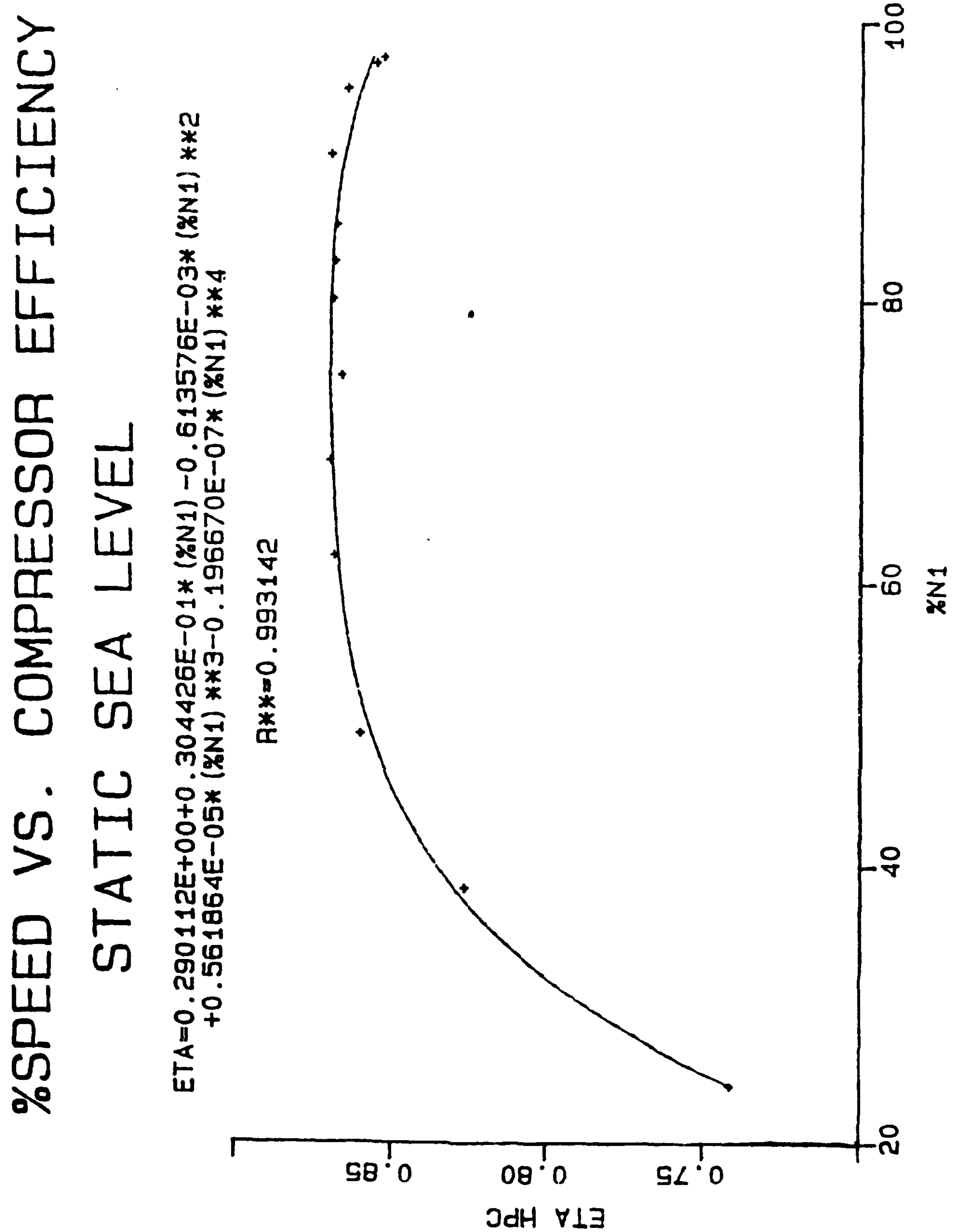


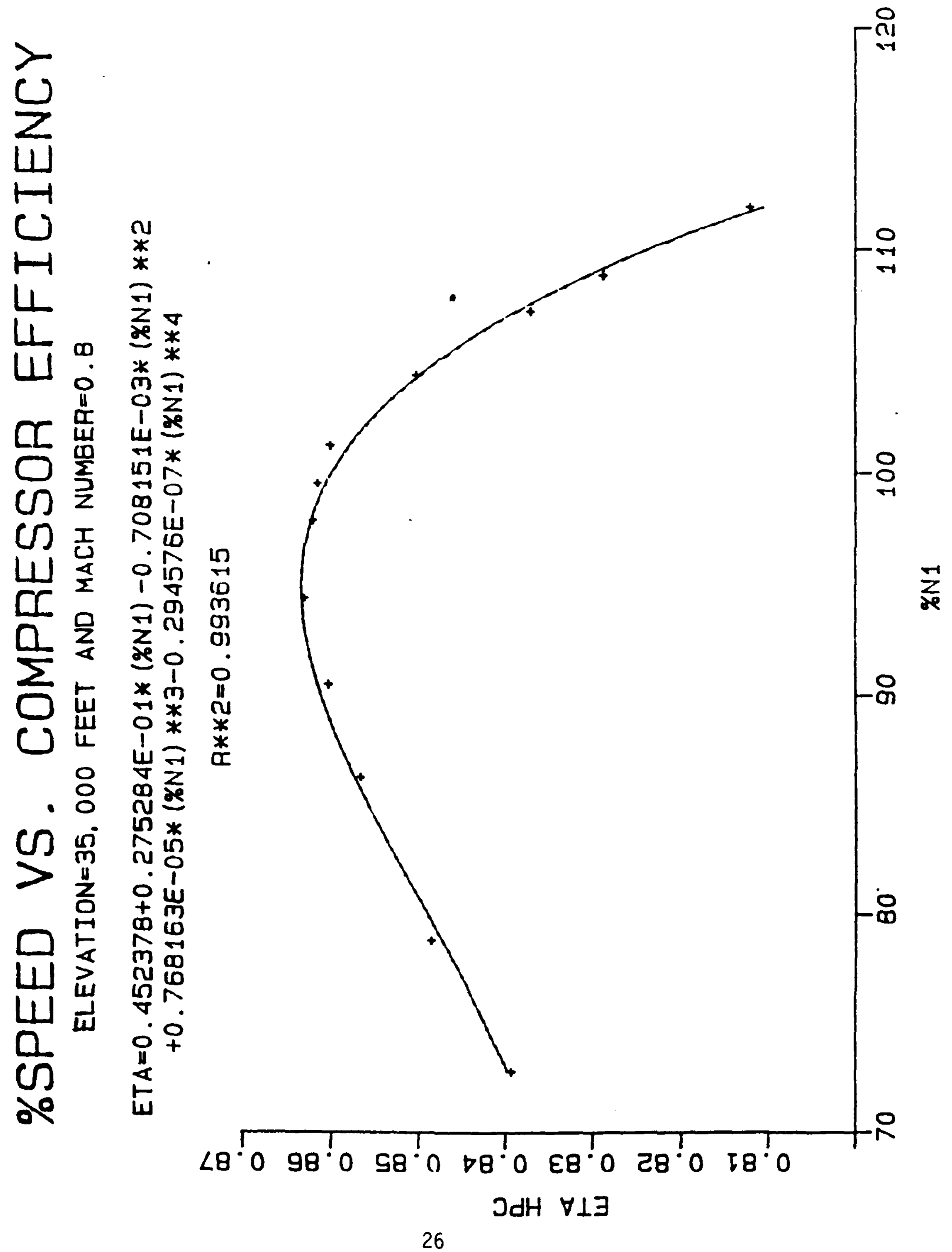
Figure 3. Seventeenth Stage, J-79

Figure 4



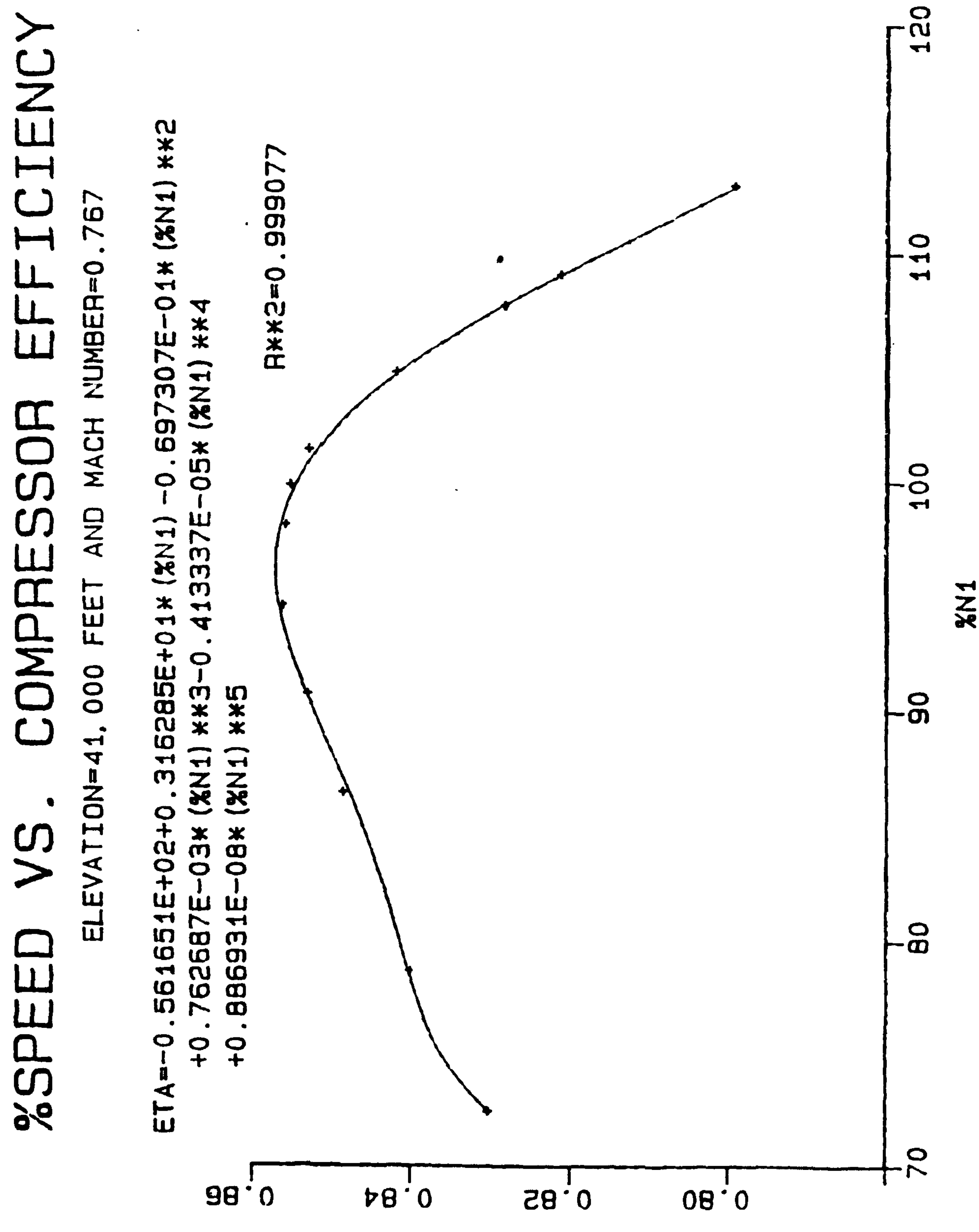
%SPEED VS. COMPRESSOR EFFICIENCY
STATIC SEA LEVEL
ETA=0.290112E+00+0.304426E-01*(%N1)-0.613576E-03*(%N1)**2
+0.561864E-05*(%N1)**3-0.196670E-07*(%N1)**4
R**=0.993142
ETA HPC
0.75
0.80
0.85
%N1
20
40
60
80
100

Figure 5



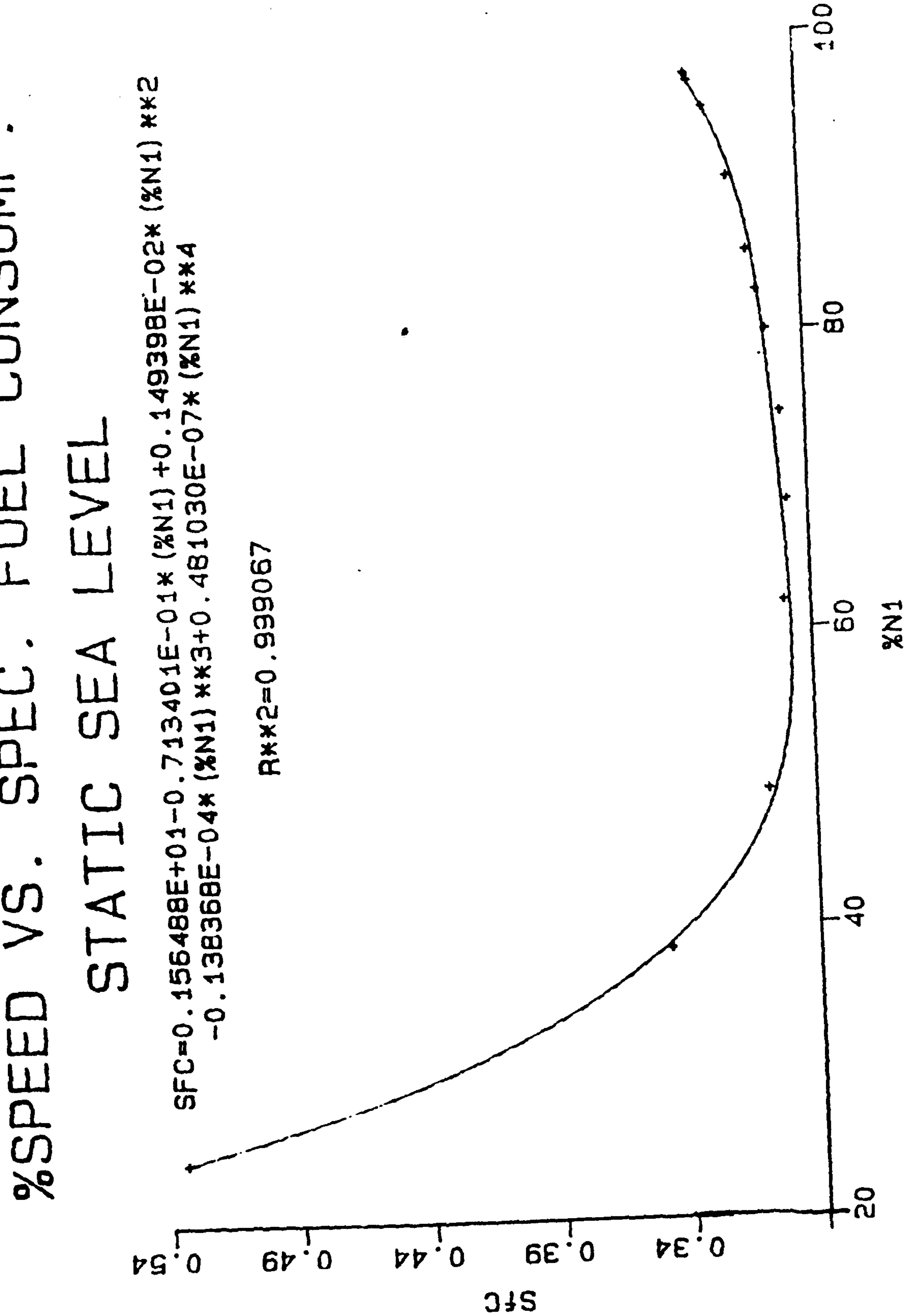
%SPEED VS. COMPRESSOR EFFICIENCY
ELEVATION=35,000 FEET AND MACH NUMBER=0.8
ETA=0.452378+0.275284E-01*(%N1)-0.708151E-03*(%N1)**2
+0.768163E-05*(%N1)**3-0.294576E-07*(%N1)**4
R**2=0.993615
ETA HPC
0.81 0.82 0.83 0.84 0.85 0.86 0.87
%N1
70 80 90 100 110 120

Figure 6



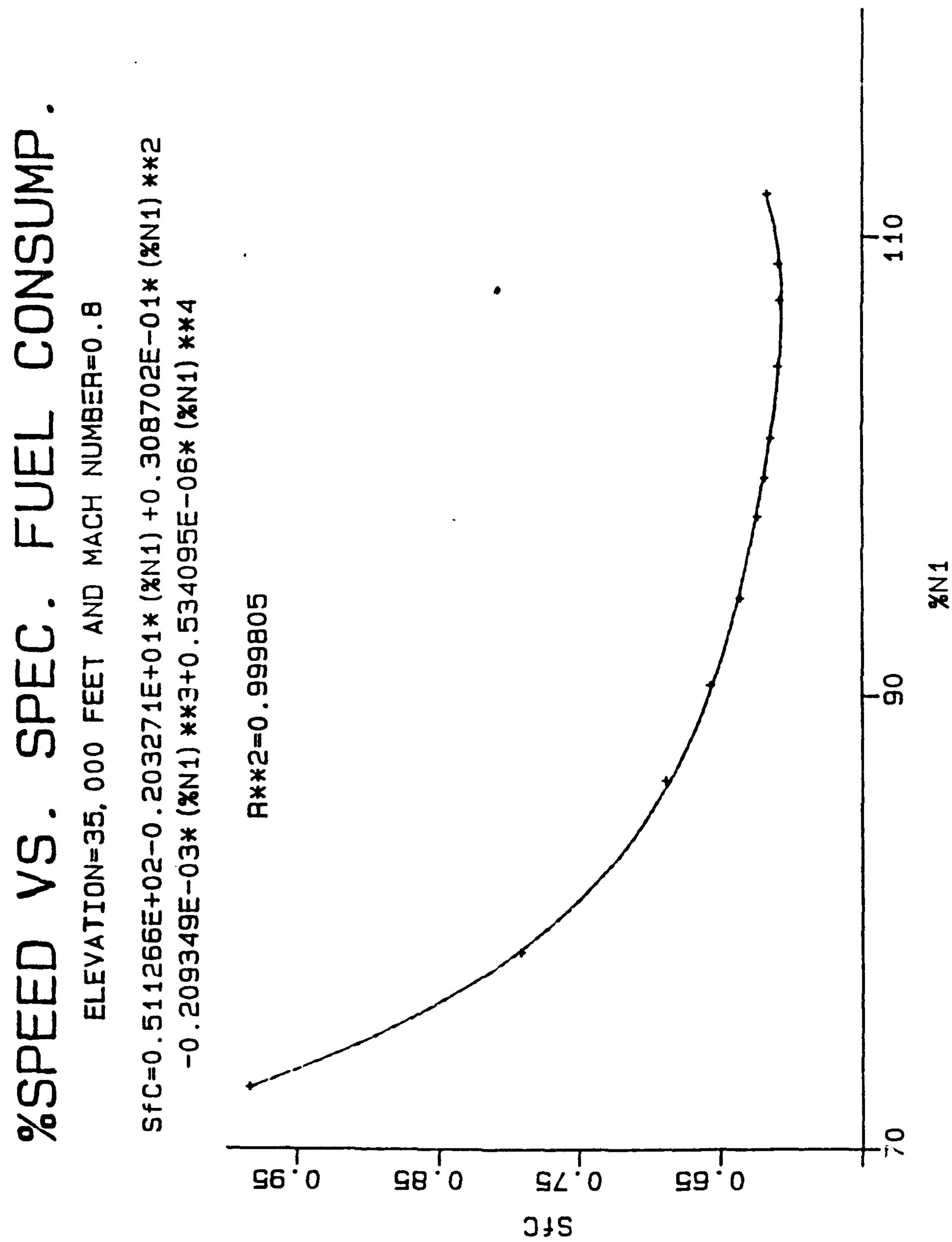
%SPEED VS. COMPRESSOR EFFICIENCY
ELEVATION=41,000 FEET AND MACH NUMBER=0.767
ETA=-0.561651E+02+0.316285E+01*(%N1)-0.697307E-01*(%N1)**2
+0.762687E-03*(%N1)**3-0.413337E-05*(%N1)**4
+0.886931E-08*(%N1)**5
R**2=0.999077
70
80
90
100
110
120
%N1
0.80
0.82
0.84
0.86
ETA HPC

Figure 7



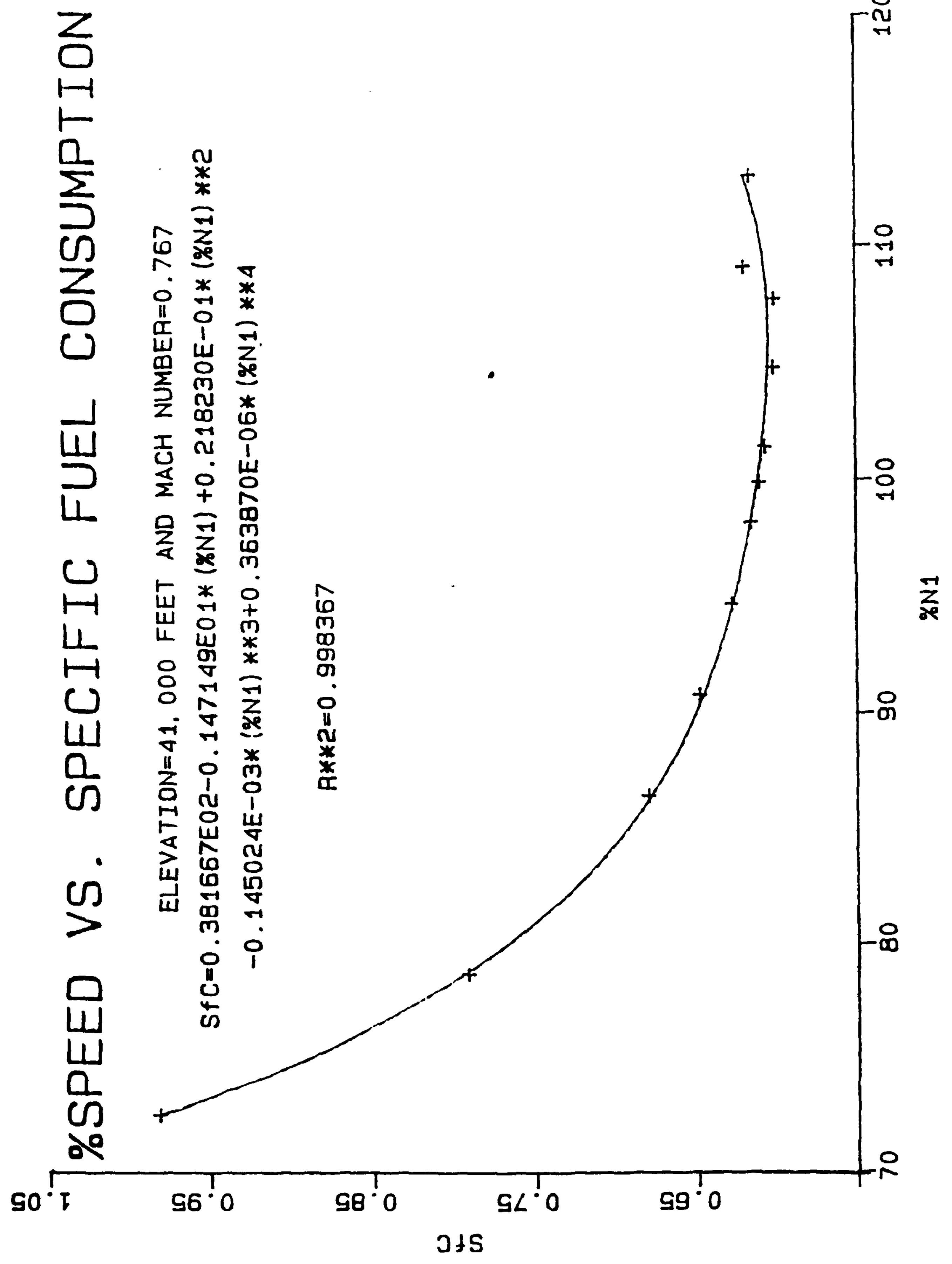
%SPEED VS. SPEC. FUEL CONSUMP.
STATIC SEA LEVEL
SFC=0.156488E+01-0.713401E-01*(%N1)+0.149398E-02*(%N1)**2
-0.138368E-04*(%N1)**3+0.481030E-07*(%N1)**4
R**2=0.999067
0.54
0.49
0.44
0.39
0.34
SFC
20
40
60
80
100
%N1

Figure 8



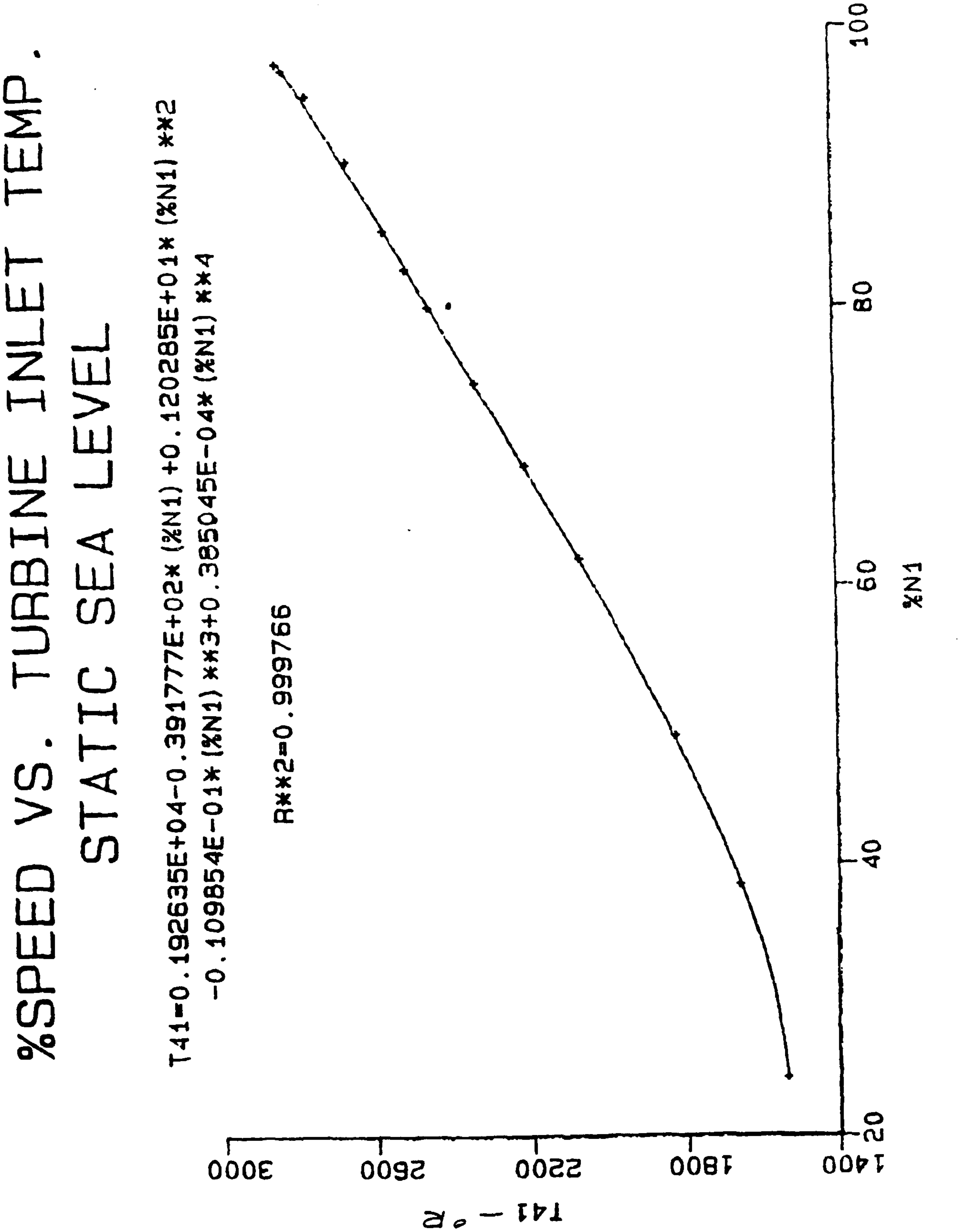
%SPEED VS. SPEC. FUEL CONSUMP.
ELEVATION=35,000 FEET AND MACH NUMBER=0.8
SfC=0.511266E+02-0.203271E+01*(%N1)+0.308702E-01*(%N1)**2
-0.209349E-03*(%N1)**3+0.534095E-06*(%N1)**4
R**2=0.999805
SfC
0.95
0.85
0.75
0.65
%N1
70
90
110

Figure 9



%SPEED VS. SPECIFIC FUEL CONSUMPTION
ELEVATION=41,000 FEET AND MACH NUMBER=0.767
SfC=0.381667E02-0.147149E01*(%N1)+0.218230E-01*(%N1)**2
-0.145024E-03*(%N1)**3+0.363870E-06*(%N1)**4
R**2=0.998367
%N1
70
80
90
100
110
120
SfC
1.05
0.95
0.85
0.75
0.65

Figure 10



%SPEED VS. TURBINE INLET TEMP.
STATIC SEA LEVEL
T41=0.192635E+04-0.391777E+02*(%N1)+0.120285E+01*(%N1)**2
-0.109854E-01*(%N1)**3+0.385045E-04*(%N1)**4
R**2=0.999766
1400
1800
2200
2600
3000
T41 — °R
20
40
60
80
100
%N1

Figure 11

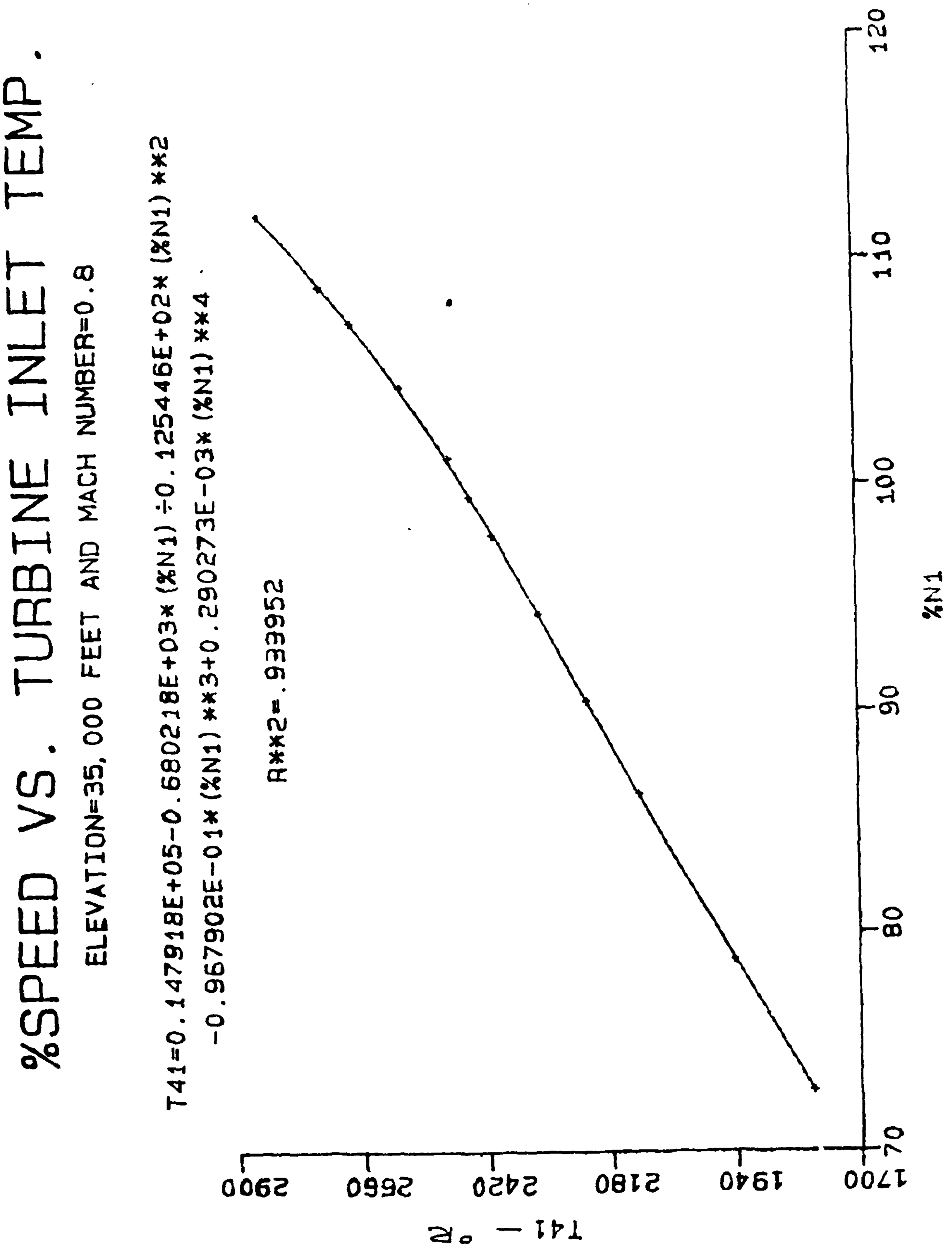

%SPEED VS. TURBINE INLET TEMP.
ELEVATION=35,000 FEET AND MACH NUMBER=0.8
T41=0.147918E+05-0.680218E+03*(%N1)+0.125446E+02*(%N1)**2
-0.967902E-01*(%N1)**3+0.290273E-03*(%N1)**4
R**2=.933952
70
80
90
100
110
120
%N1
1700
1940
2180
2420
2660
2900
T41 — °R

Figure 12

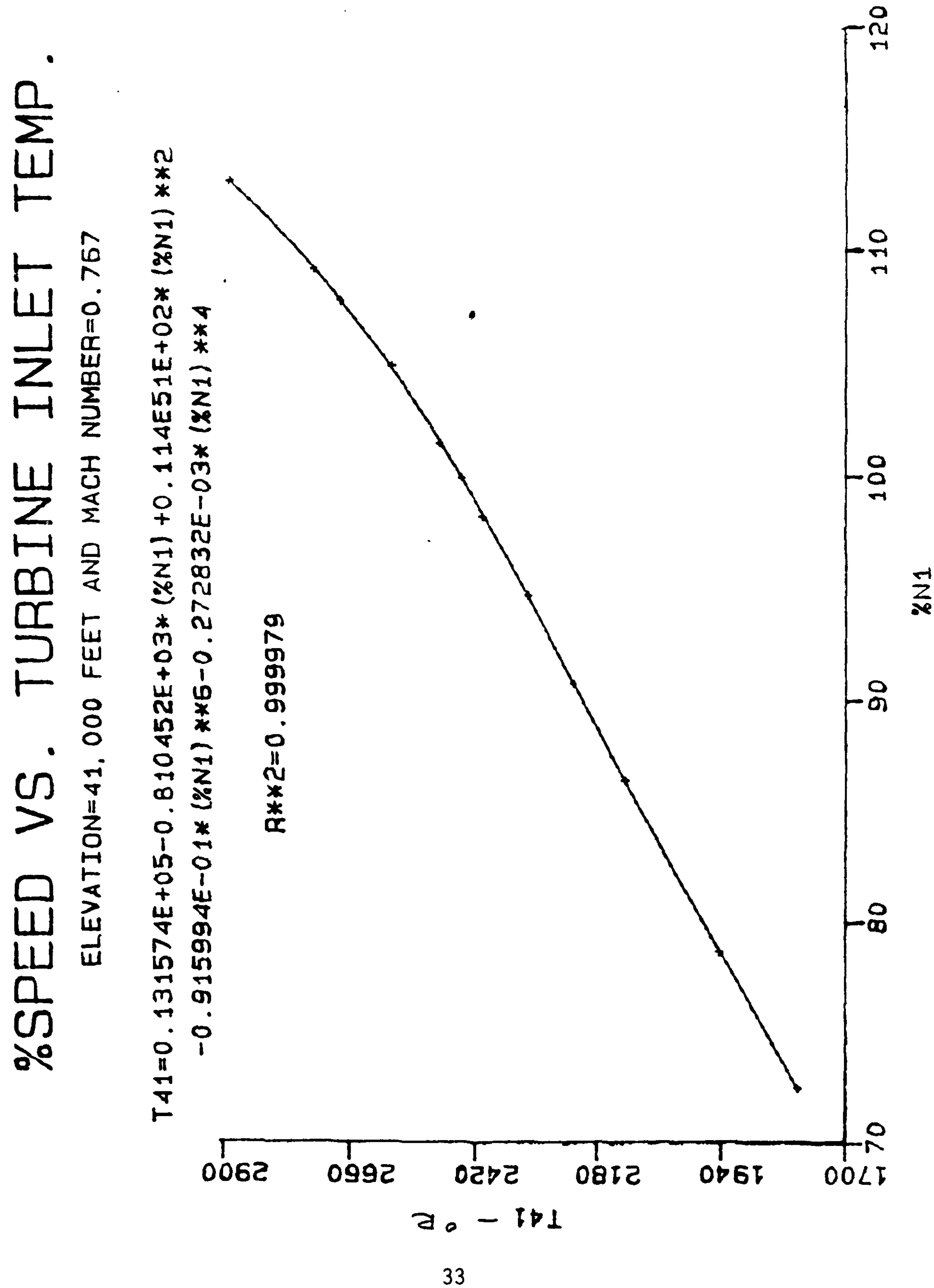
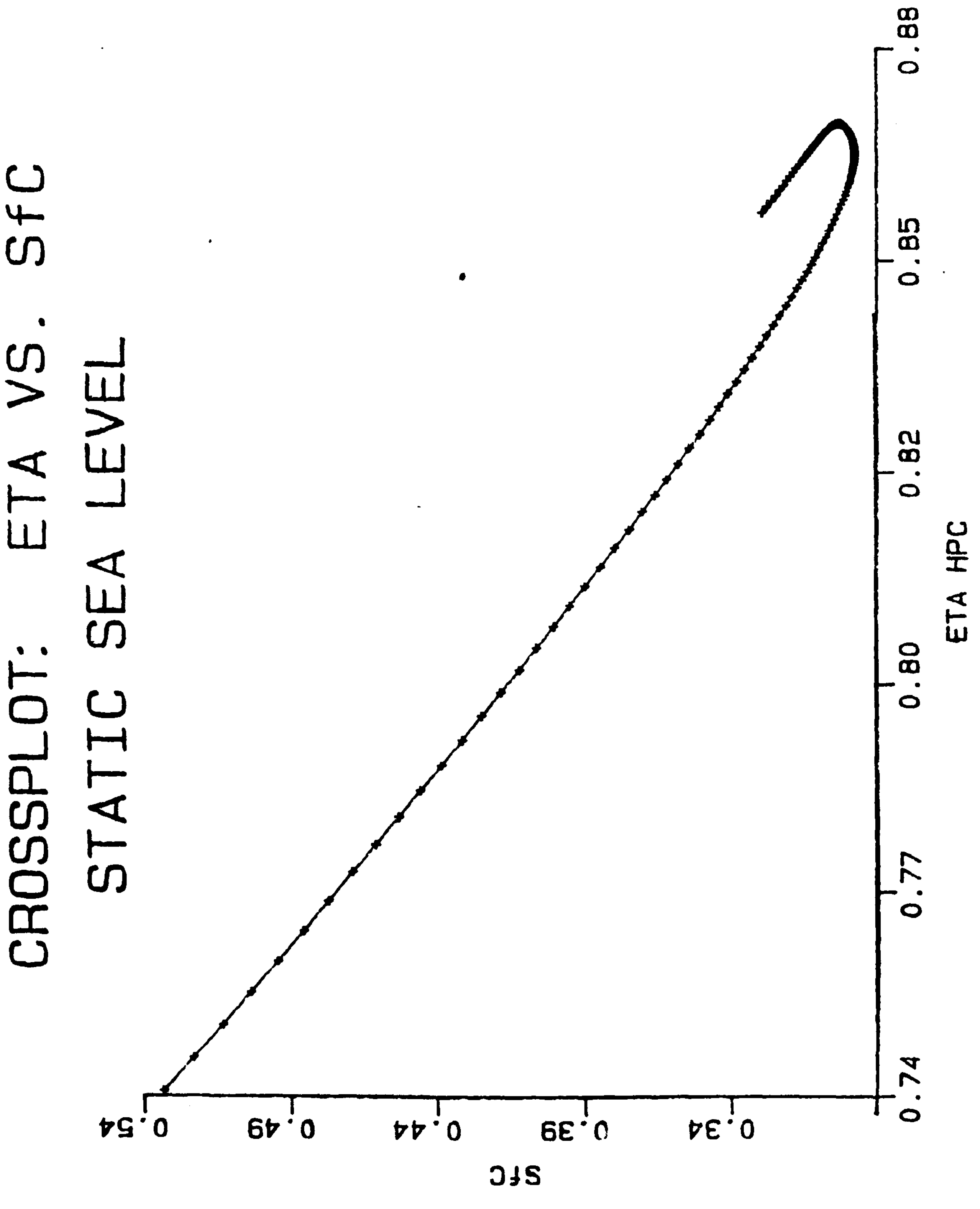

%SPEED VS. TURBINE INLET TEMP.
ELEVATION=41,000 FEET AND MACH NUMBER=0.767
T41=0.131574E+05-0.810452E+03*(%N1)+0.114E51E+02*(%N1)**2
-0.915994E-01*(%N1)**6-0.272832E-03*(%N1)**4
R**2=0.999979
2900
2660
2420
2180
1940
1700
T41 — °R
70
80
90
100
110
120
%N1

Figure 13



CROSSPLOT: ETA VS. SFC
STATIC SEA LEVEL
ETA HPC
0.74
0.77
0.80
0.82
0.85
0.88
SFC
0.54
0.49
0.44
0.39
0.34

Figure 14

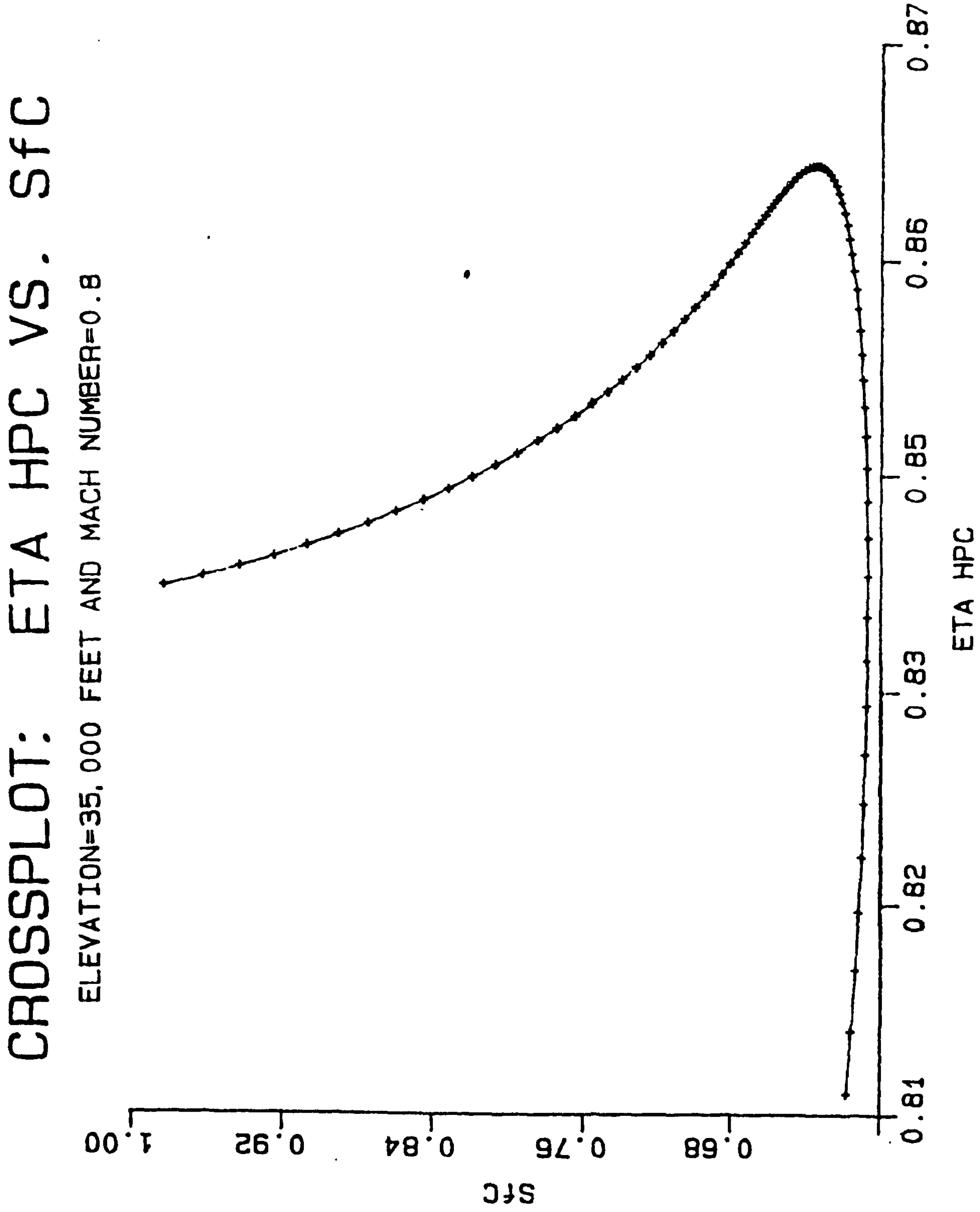

CROSSPLOT: ETA HPC VS. SfC
ELEVATION=35,000 FEET AND MACH NUMBER=0.8
ETA HPC
0.81
0.82
0.83
0.85
0.86
0.87
SfC
0.68
0.76
0.84
0.92
1.00

Figure 15

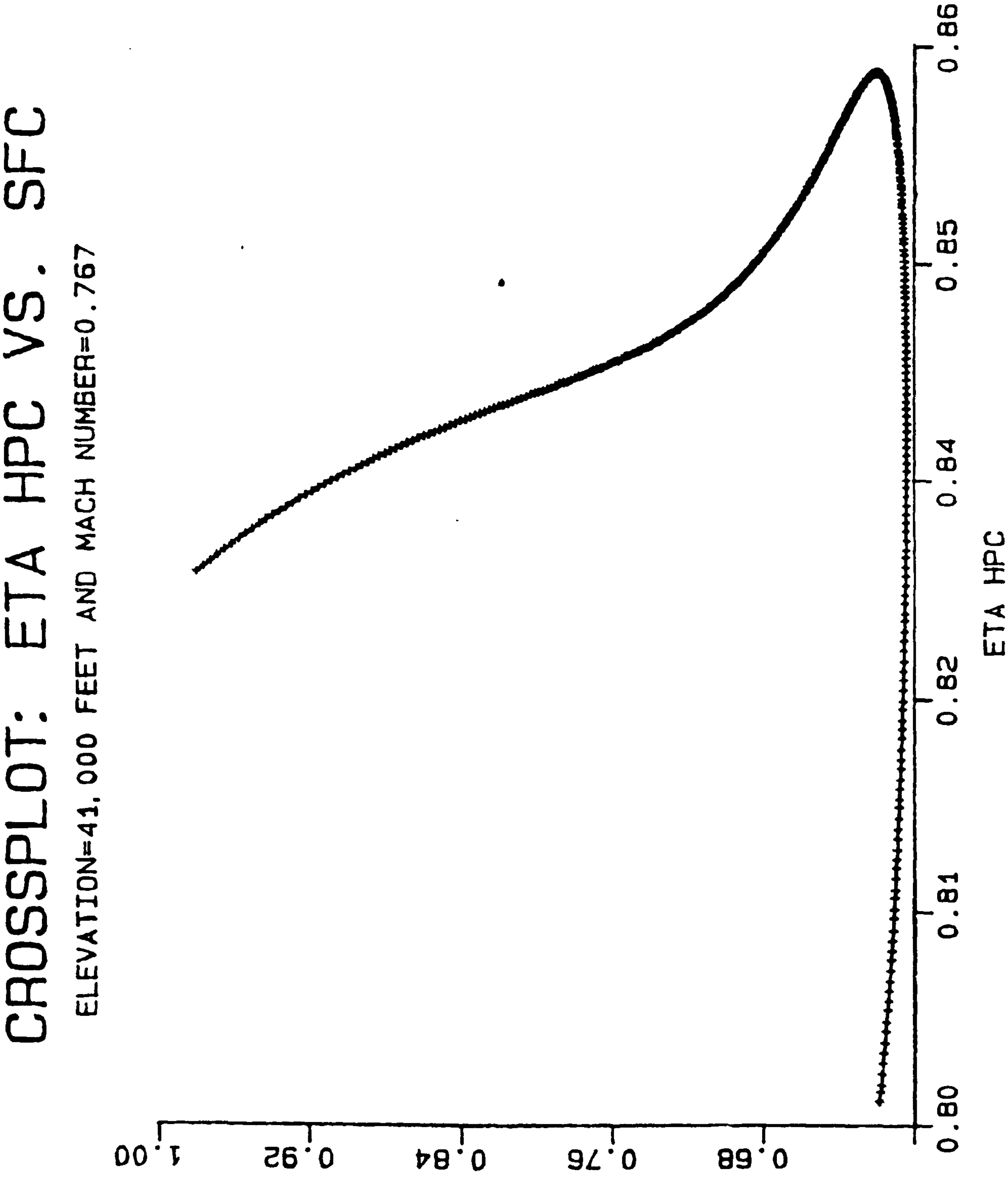

CROSSPLOT: ETA HPC VS. SFC
ELEVATION=41,000 FEET AND MACH NUMBER=0.767
ETA HPC
0.80
0.81
0.82
0.84
0.85
0.86
SFC
0.68
0.76
0.84
0.92
1.00

Figure 16

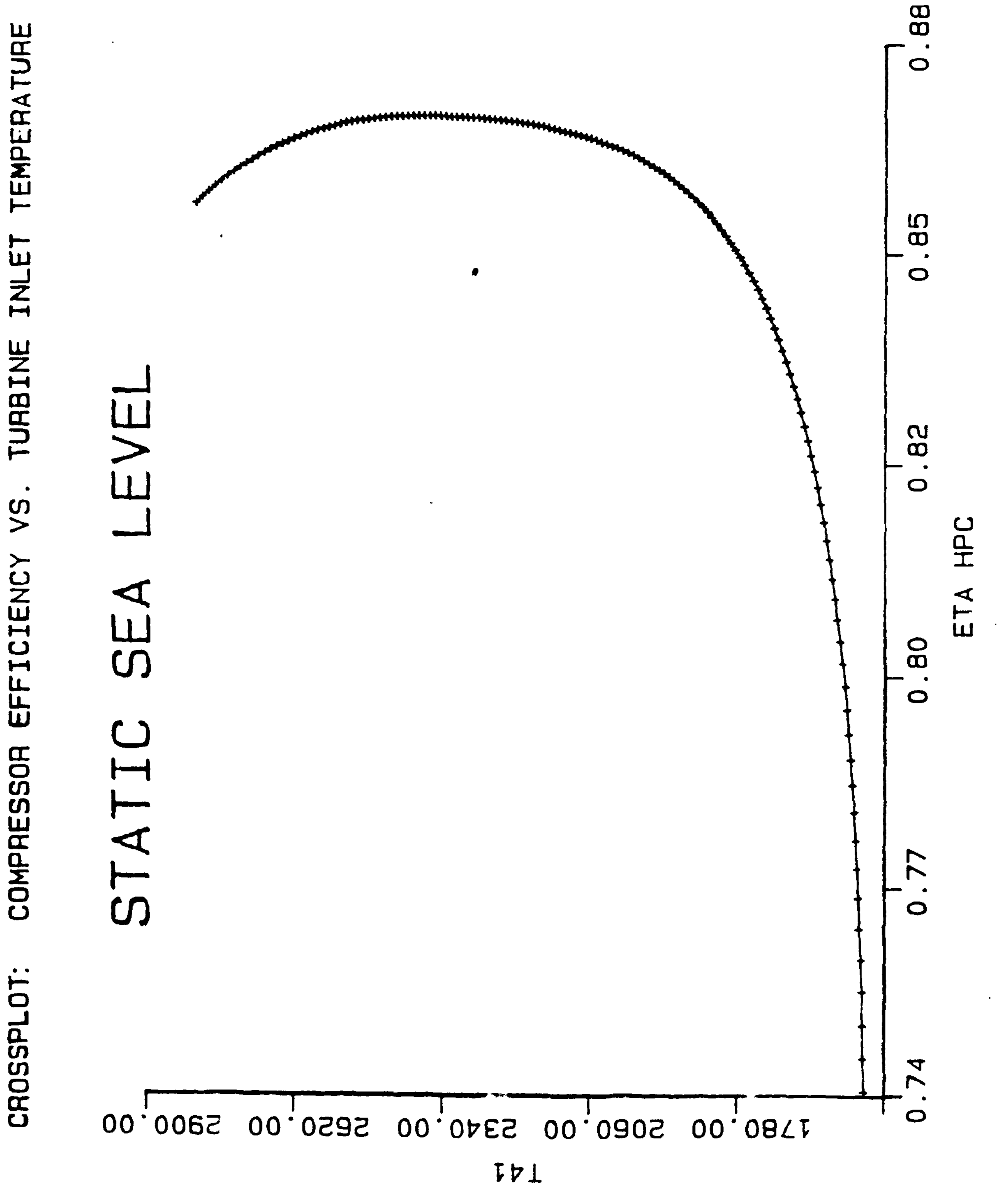
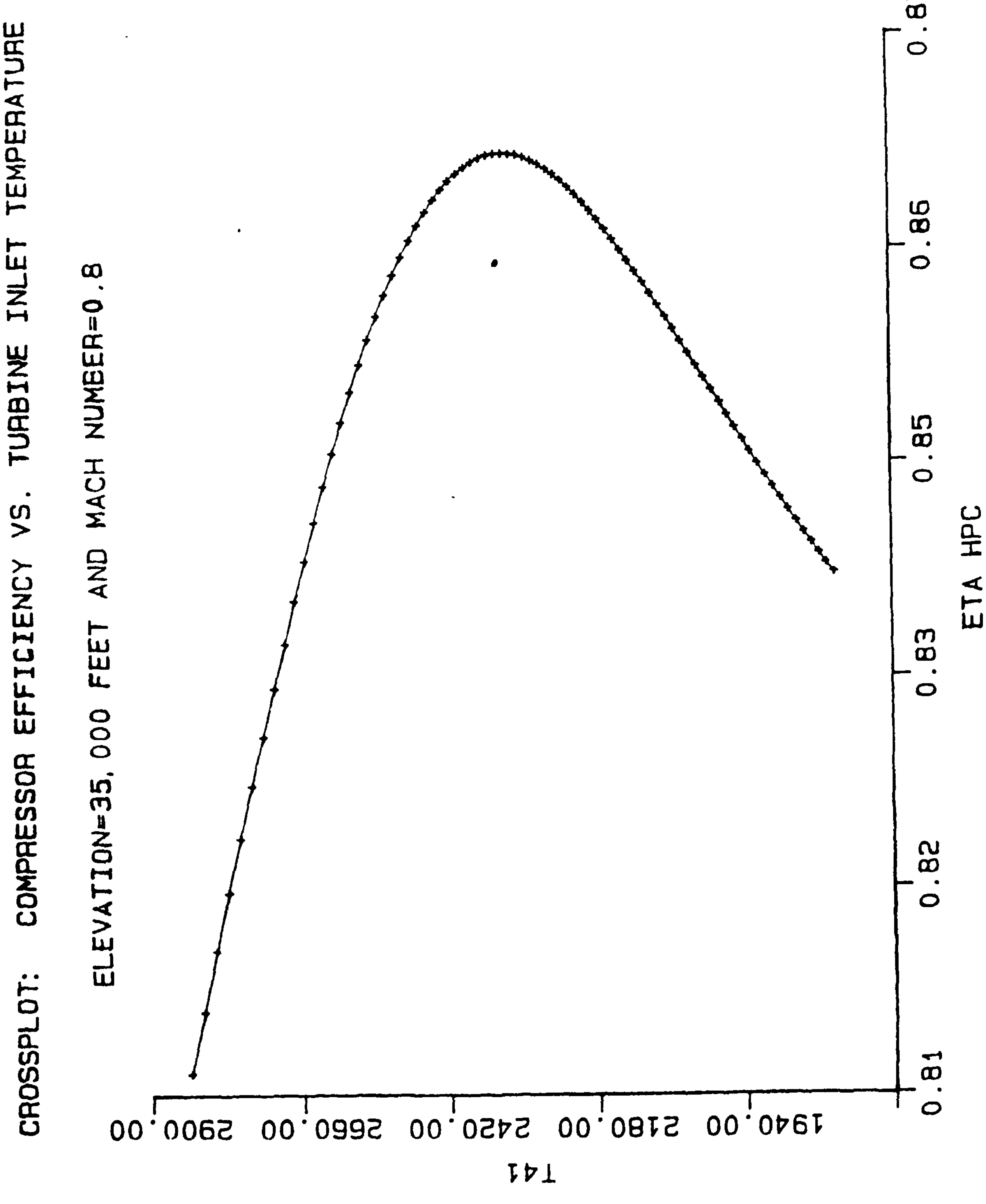
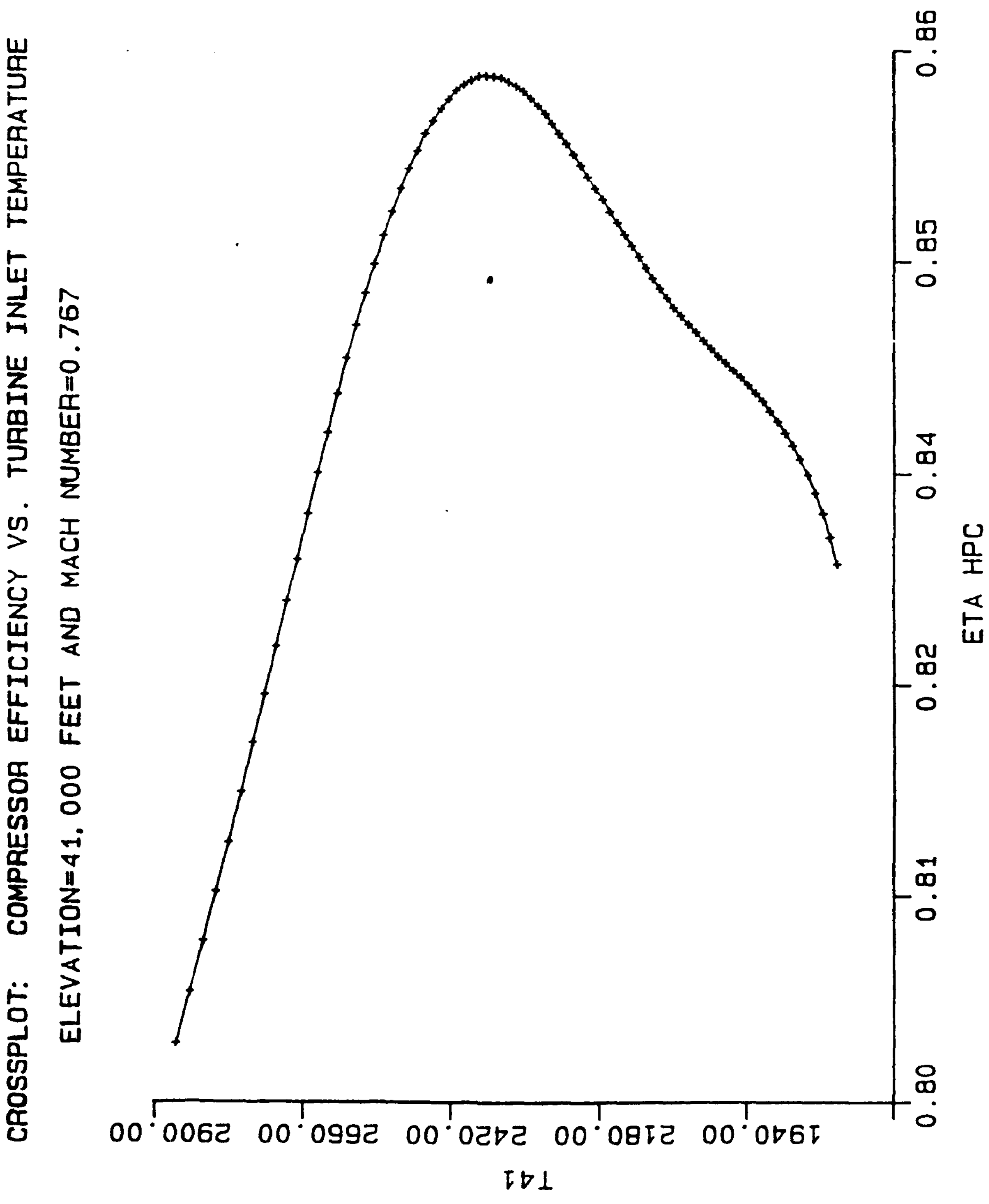

CROSSPLOT: COMPRESSOR EFFICIENCY VS. TURBINE INLET TEMPERATURE
STATIC SEA LEVEL
ETA HPC
0.74
0.77
0.80
0.82
0.85
0.88
T41
1780.00
2060.00
2340.00
2620.00
2900.00

Figure 17



CROSSPLOT: COMPRESSOR EFFICIENCY VS. TURBINE INLET TEMPERATURE
ELEVATION=35,000 FEET AND MACH NUMBER=0.8
0.81
0.82
0.83
0.85
0.86
0.87
ETA HPC
2900.00
2660.00
2420.00
2180.00
1940.00
T41

Figure 18



CROSSPLOT: COMPRESSOR EFFICIENCY VS. TURBINE INLET TEMPERATURE
ELEVATION=41,000 FEET AND MACH NUMBER=0.767
0.80
0.81
0.82
0.84
0.85
0.86
ETA HPC
2900.00
2660.00
2420.00
2180.00
1940.00
T41

List of Tables

Table 1

Compressor Blade and Vane Specification Drawings

Pratt & Whitney TF30-P-9

Stage	Blade Dwg. No.	Vane Dwg. No.
1	618501	531351
2	618502	616352
3	618503	577853
4	618204	704554
5	618205	537855
6	618206	537856
7	591907	479357
8	618208	557958
9	618209	
10	576710*	564260
11	576711	555561
12	576712	649762
13	576713	649763
14	576714	649764
15	576715	649765
16	576716	649766

Rotor and Stator Front Compressor Assembly Drawing 2181893
Rotor and Stator Rear Compressor Assembly Drawing 2184553

Pratt & Whitney TF33-P-7

Stage	Blade Dwg. No.	Vane Dwg. No.
1	529601	
2	475402	625652 & 454852
3	475203	454853 (456453-vane & shroud assembly)
4	372004	454854
5	483705	479055
6	389906	360156
7	389907	360157
8	389908	360158
9	389909	495259 & 495359
10	506510	454460
11	506511	454461
12	506512	454462
13	462813	477053
14	464214	477053
15	464215	477053
16	464316	

Rotor and Stator Front Compressor Assembly Drawing 434498
Rotor and Stator Rear Compressor Assembly Drawing 434499

Table 1 (Continued)

Compressor Blade and Vane Specification Drawings

General Electric TF39

Stage	Blade Dwg. No.	Vane Dwg. No.
1	K157P02	K001P09
2	K256P06	K172P05
3	K350P25	K202P02
4	K451P22	K390P04
5	K552P25	K403P02
6	K667P17	K647P02
7	K775P13	K779P15
8	K841P17	K109P01
9	K107P25	K980P17
10	K043P28	K081P15
11	K144P17	K182P07
12	K245P17	K207P21
13	K326P01	K310P15
14	K427P01	K412P27
15	K547P38	K513P21
16	K648P34	K688P17

General Electric J79-15

Stage	Blade Dwg. No.	Vane Dwg. No.
1	111R107	638E655
2	111R108	638E640
3	111R109	638E641
4	111R110	638E642
5	111R111	638E643
6	111R111	638E643
7	111R112	515D741
8	111R112	515D741
9	111R112	515D742
10	111R113	515D743
11	111R113	515D744
12	111R113	515D745
13	111R114	515D746
14	111R114	515D747
15	111R115	515D748
16	111R115	515D749
17	111R115	111R193 (includes outlet guide vane)

Engine Assembly Drawing	107R587
Compressor Assembly Drawing	111R187

Table 1 (Continued)

Compressor Blade and Vane Specification Drawings

Allison T56-A-15

Stage	Blade Dwg. No.	Vane Dwg. No.
1	6809081	6859601
2	6809082	6859602
3	6809083	6859603
4	6809084	6859604
5	6809085	6859605
6	6809086	6859606
7	6809087	6859607
8	6809088	6859608
9	6809089	6859609
10	6809090	6859610
11	6809091	6859611
12	6809092	6859612
		6859613
		6859614

Compressor Vane Assembly 6873624
(Air Inlet - Anti-Icing)

Table 2

The following is a listing of compressor blade and vane re-work production for the month of August 1988 at Tinker AFB, OK.

The "number re-worked" indicates those blades/vanes that could be reworked within T.O. limits and the "number condemned" indicate those exceeding T.O. re-work limits - not including condemnation due to cracks.

Pratt & Whitney TF30

Part No.	No. Re-worked	No. Condemned
521155	887	37
556703		3
576711	459	0
576713	493	0
576715	105	0
577902		5
578516	399	26
616502		5
658516	781	516
777503		10
2180501		16
2180601		3
	3124	611

Pratt & Whitney TF33

Part No.	No. Re-worked	No. Condemned
364911	350	3
364913	73	0
372004	1838	49
372005	267	14
389906	967	20
389907	913	68
389908	1092	12
389909	4705	80
404501	12	21
430401	50	0
475203	436	0
483705	216	1
505602	567	19
694301	1012	19
	12498	306

Table 2 (Continued)

Allison TF-41

Part No.	No. Re-worked	No. Condemned
6860014	245	0
6860015	418	6
6863575	573	13
6863576	890	17
6863947	1450	87
6863948	927	156
6863949	923	123
6863950	1082	142
6866282	223	13
6866286	979	15
6869628	140	2
6892153	650	6
Short Vanes	708	23
Long Vanes	464	27
	9889	673

Pratt & Whitney J-57

Part No.	No. Re-worked	No. Condemned
251802	291	42
251803	334	0
251805	801	82
254510	481	116
254511	866	43
254512	990	48
254513	415	96
254514	1360	140
254515	2171	52
277706	827	48
277707	1294	279
277708	619	107
277709	644	13
312701	474	28
380607	108	0
	12875	1284

Table 2 (Continued)

General Electric J-79

Part No.	Blade-Stage	No. Re-worked	No. Condemned
111R107	1	265	11
111R108	2	365	13
111R109	3	860	45
111R110	4	1773	72
111R111	5	769	60
111R111	6	952	54
111R112	7	1263	97
111R112	8	0	0
111R112	9	1244	12
111R113	10	3424	542
111R113	11	258	43
111R113	12	0	0
111R114	13	911	108
111R114	14	392	65
111R115	15	0	0
111R115	16	116	33
111R115	17	2924	242
		15516	1397

Part No.	Vane-Stage	No. Re-worked	No. Condemned
628E640	2	914	61
638E641	3	780	37
638E642	4	1083	10
638E643	5	443	0
638E643	6	792	19
515D740	7	1441	389
515D741	8	482	949
515D742	9	240	458
515D743	10	1486	183
515D744	11	2939	468
515D745	12	2335	224
515D746	13	2892	480
515D747	14	762	341
515D748	15	1319	960
515D749	16	2543	774
111R193	17	783	204
		20529	5557

Table 3

The following GE-TF39 Compressor Blade re-work data was obtained from SA-ALC/MMPRAE

Note: Re-work of all TF39 Compressor Vanes and Blade Stages 9, 10, 13 and 14 are "Contracted Out".

Stage	QPA	Cost(New)	No. Bought Annually	Repair Cost Annually	No. Repaired
1	36	$322.28	1848	$78.00	2174
2	40	106.08	576	33.25	211
3	42	82.11	288	25.15	1134
4	45	72.98	612	27.81	607
5	48	66.09	612	22.25	1608
6	54	46.20	840	21.29	2111
7	56	46.09	840	21.29	2829
8	64	38.85	1776	21.29	1853
9	66	42.94	720		
10	66	38.10	456		
11	76	36.38	1656	20.66	8765
12	76	36.38	1656	20.66	3602
13	76	43.50	1764		
14	76	49.79	828		
15	76	24.29	1248	19.52	773
16	76	32.20	1200	19.92	619

Vane costs and "annual buys" are listed for comparison purposes.

Stage	Cost	Annual Buy	Stage	Cost	Annual Buy
1	$126.29	1860	9	$31.61	1692
2	111.67	6648	10	24.96	900
3	123.91	3780	11	24.91	1548
4	81.00	6636	12	25.84	2136
5	73.92	8748	13	31.49	984
6	59.52	6540	14	24.29	600
7	29.12	1188	15	23.32	720
8	31.61	1692	16	26.88	1872

Allison TF41

Vanes - Low Pressure Compressor

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1	23006085	0	2	369
2	6860185	411	8	323
3	6860188	239	9	352
OGV	6869580	0	0	6
OGV	6869808	0	20	17

Stage	Unit 1	Cost 2	Last Three Buys (3)	Re-work Cost
1	$47,621.00	$47,621.00	$65,881.00	$2,015.00
2	681.68	493.25	433.46	
3	116.92	114.01	114.01	
OGV	9,211.85	12,474.56	24,254.46	
OGV	13,066.65	13,066.65	18,069.55	605.00

Blades - Low Pressure Compressor

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1	6892422	0	3	697
2	6897201	88	14	0
3	6897202	207	4	34

Stage	Unit 1	Cost 2	Last Three Buys (3)	Re-work Cost
1	$1,201.00	$1,220.00	$1,388.00	$ 467.00
2	559.20	848.80	848.80	
3	215.49	215.49	477.95	

Allison TF 41 (Continued)

Vanes - Intermediate Compressor

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1	6869579	0	20	16
2	6860185	411	8	323

Stage	Unit 1	Cost 2	Last Three Buys (3)	Re-work Cost
1	$2,800.34	$2,765.35	$3,928.15	$ 727.00
2	681.68	493.25	433.46	

Blades - Intermediate Compressor

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1	6860014	32	2	0
2	6860015	44	3	0

Stage	Unit 1	Cost 2	Last Three Buys (3)	Re-work Cost
1	$ 103.63	$ 103.63	$ 115.67	$ 40.00
2	21.12	21.12	206.41	40.00

Vanes - High Pressure Compressor

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1	6869204	0	1	0
2	6869205	0	0	0
3	6869206	0	1	0
4	6869207	0	0	0

Allison TF41 (Continued)

Vanes - High Pressure Compressor (Continued)

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
5	6869208	0	0	0
6	6869209	0	1	0
7	6894540	2873	0	2580
8	6894545	1928	0	1512
9	6869235	2534	0	1505
10	6869240	5514	0	4055
OGV-11	6869245	2921	1	2289

Stage	Unit 1	Cost 2	Last Three Buys (3)	Re-work Cost
1	$ 515.45	$ 592.73	$ 455.47	$ 388.00
2	556.43	656.49	496.40	388.00
3	634.34	659.91	523.91	390.00
4	559.83	499.44	499.44	390.00
5	1,840.94	1,997.00	1,902.00	
6	1,140.43	1,813.00	1,870.88	
7	44.23	43.77	47.60	
8	44.20	45.95	47.59	
9	20.32	25.27	34.66	
10	38.62	37.54	41.88	
OGV-11	41.42	39.81	44.30	

Blades - High Pressure Compressor

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1				
2	6863947	2320	24	4375
3	6863948	1332	19	3170
4	6863949	2534	18	3793
5	6863950	1312	9	2764
6	6894550	2712	0	2458
7	6897245	5292	0	3946
8	6869230	338	0	775
9	6869258	0	9	8164
10	6869250	0	13	8065
11	6869256	0	10	10476

Allison TF41 (Continued)

Blades - High Pressure Compressor (Continued)

Stage	Unit 1	Cost 2	Last Three Buys (3)
1			
2	$ 35.87	$ 27.96	$ 36.60
3	33.82	35.97	35.97
4	32.24	30.50	37.94
5	33.91	34.60	37.25
6	40.00	48.11	49.23
7	45.86	57.10	31.73
8	22.51	20.33	25.28
9	36.30	42.02	55.30
10	36.21	45.15	47.02
11	44.75	48.75	46.42

General Electric J79-15

Blades

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1	111R107P7	(84) 19140	7	437
2	111R108P7	(84) 2000	5	70
3	111R109P7	(84) 2833	4	996
4	111R110P7	(83) 4785	2	2194
5	111R111P23	(87) 11123	88	6797
6	111R112P24	(86) 7706	80	6683
7	111R112P25	(87) 22550	43	9096
8	111R112P26	(87) 15820	76	8225
9	111R112P27	(87) 12847	78	9480
10	111R113P25	(87) 188777	78	12513
11	111R113P26	(87) 17570	67	11283

General Electric J79-15 (Continued)

Blades (Continued)

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
12	111R113P27	(87) 17423	72	13325
13	111R114P13	(87) 22868	83	14837
14	111R114P14	(87) 42453	96	16240
15	111R115P19	(87) 23673	71	13905
16	111R115P20	(87) 36096	82	15322
17	111R115P21	(87) 33747	77	19763

Stage	Unit 1	Cost 2	Last Three Buys (3)
1	(81) 76.48	(81) 97.43	(84) 111.17
2	(80) 78.37	(83) 101.12	(84) 101.12
3	(82) 76.07	(83) 75.76	(84) 75.76
4	(80) 54.30	(83) 76.25	(83) 76.25
5	(84) 33.00	(86) 33.00	(87) 33.00
6	(84) 51.50	(85) 33.00	(86) 33.00
7	(84) 41.20	(86) 27.00	(87) 25.00
8	(86) 29.00	(87) 29.00	(87) 26.00

General Electric J79-15 (Continued)

Blades (Continued)

Stage	Unit 1	Cost 2	Last Three Buys (3)
9	(87) 26.00	(87) 26.00	(87) 26.00
10	(84) 35.69	(87) 18.00	(87) 18.00
11	(85) 22.01	(87) 17.65	(87) 17.65
12	(85) 22.01	(87) 18.65	(87) 18.65
13	(86) 16.65	(87) 15.85	(87) 16.03
14	(84) 30.21	(87) 15.75	(87) 14.90
15	(84) 24.39	(87) 15.65	(87) 15.65
16	(85) 18.95	(87) 16.50	(87) 15.75
17	(85) 18.75	(87) 16.40	(87) 15.70

*Year Last Bought Price in Parentheses

General Electric J79-15

Vanes

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
1-15	638E655G4	(85) 3957	5	228
1-17	638E222P4	(85) 3172	16	691
2	638E640P4	(84) 5133	3	480
3	638E224P2	(84) 5055	22	1335
4	638E225P2	(85) 8765	29	2035
5	638E643P7	(85) 10400	5	2359
6	638E643P8	(85) 6823	13	1848

General Electric J79-15 (Continued)

Vanes (Continued)

Stage	Part No.	Annual Purchase	Condemnation Rate%	Annual Depot Replacement
7	7055M23G01	(85) 39683	5	1984
8	515D741G4	(78) 1069	55	1661
9	515D742G7	526	67	764
	515D742G8	1313	49	1201
10	515D743G4	5087	38	6193
11	515D744G4	4121	50	6934
12	515D745G4	(74) 3179	70	5450
13	515D746G4	(77) 3099	75	2596
14	515D747G4	3558	43	2926
15	515D748G4	(77) 5043	67	4766
16	515D749G4	(78) 2569	44	2305
17	111R193G2	(77) 3910	68	3746

Stage	Unit 1	Cost 2	Last Three Buys (3)	Annual Field Replacement
1-15	(83) 342.21	(83) 342.21	(85) 325.00	65
1-17	(83) 127.40	(83) 126.50	(85) 91.05	43
2	(83) 134.10	(83) 69.75	(84) 125.00	154
3	(85) 121.05	(83) 121.05	(83) 85.33	184
4	(83) 67.25	(85) 88.57	(85) 86.83	
5	(83) 85.00	(84) 95.00	(85) 65.35	283
6	(83) 83.60	(83) 83.60	(84) 91.10	241
7	(83) 41.92	(83) 37.50	(84) 36.68	
8	(78) 15.46	(78) 16.40	(78) 9.84	214

General Electric J79-15 (Continued)

Vanes (Continued)

Stage	Unit 1	Cost 2	Last Three Buys (3)	Annual Field Replacement
9				141 111
10				1565
11				378
12	(73) 3.13	(74) 3.03	(74) 3.13	331
13	(72) 6.53	(72) 10.33	(75) 3.50	503
14				632
15	(76) 5.90	(77) 7.02	(77) 7.02	277
16	5.19	7.18	(78) 8.06	264
17	(77) 11.85	(77) 11.84	(77) 12.50	164

Selected References

Birkler, J.L., and Nelson, J.R., "Aircraft Turbine Monitoring Experience: An Overview and Lessons Learned from Selected Case Studies," Rand Report NO. R-2440-AF. 1980.

Bolick, R.P., and Mancini, J.M., "Northwest JT8D Evaluation of Sermetel 'W' Coated Stators." Pratt and Whitney Aircraft Group, 1978.

Gieleghem, R.A., "CF-6 High Pressure Compressor Performance Management." General Electric Gas Turbine Division, March, 1987.

Kelley, S.E., "Resume of Engineering evaluation of Manufacturing's 'Cut and Burnish' Process for Sermetel 'W', PWA 110-2 Coated Stators and Effect on Engine TSFC." Pratt and Whitney Internal Correspondence: Kelley, S.E., to Acker, W.L., 20 December 1977.

Kimball, J.C., "Effect of Sermetel 'W' Coating of J73P Production Engine Compressor Stators." Pratt and Whitney Internal Correspondence, Kimball, J.C., to McMahon, M.P., 23 July 1976.

Mullan, D., "TF-39 Performance Analysis," Aircraft Engine Group, General Electric, Lynn, MA/Cincinnati, OH, May 1987.

Ross, E. (Capt USAF), "The Silver Streak Effort," Demonstration of Jet Engine Performance Improvements by Smoothing Compressor Airfoil Surfaces. Oklahoma City Air Logistics Center, 1979.

"Sermetel 'W' for Surface Repair of Compressor Vane and Shroud Assemblies - J57/J75/TF-33 Engines." Pratt and Whitney Report to Commander, OC-AMA, Tinker AF OK, 25 July 1973.

Stiles, R.J., "Roughness Effects in Axial Flow Compressors - An Empirical Model." Note: Source of publication of report by Captain R.J. Stiles, USAF, date, unknown.

Syphers, G.N., "Results of P/L 13225 Sermetel 'W' Stator Coatings, JT3D-3B and JT3D-7." Pratt and Whitney Internal Correspondence, Syphers, G.N., to Yenker, C.E., 14 February 1977.

Urban, L.A., "Gas Path Analysis of Commercial Aircraft Engines." Pratt and Whitney (Presented at 11th AIDS Symposium DFVLR AIDS Study Group, Cologne, Germany, 22-24 September 1981).

Volponi, A.J., "Gas Path Analysis - An Approach to Engine Diagnostics." Pratt and Whitney ESP. 8222 (Presented to 35th Symposium, Mechanical Failures Prevention Group, Gaithersburg, MD, 20-22 April 1982).

Werner, F.T., "Sermetel 'W' Coated J-57 Compressor." Headquarters SAC, Engineering Report No. P-185, 30 July 1981.

"A Feasibility Study on Improving the Thrust Specific Fuel Consumption for the TF-33-P-7, 7A Engines," (A Technical Planning Estimate). Pratt and Whitney Aircraft Group (GPD), 1980.

"C-5 Propulsion System Study," Final Engineering Report for the period 21 September 1987-31 March 1988; Defense Logistics Support, General Atomics, Project: F4 1608-86-D-A113-3-3A276, May 1988.

"Test Results of a Redesigned Low-Pressure--Intermediate Pressure Compressor." Detroit Diesel Allison (Division of General Motors Corporation), Date unknown.

"TF-33 Fuel Consumption Improvement Feasibility." United Technologies, Pratt and Whitney (GPD), 1982 (?).

Urban, L.A., "Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines," ASME Paper No. 74-GT-6, 1974.